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Report AMXTH-TE-CR-86101

Installation Restoration Program
Environmental Technology Department

Contract DAAK 11-85-D-0007

Task Order 7
Interim Technical Report
Heavy Metal Contaminated Soil
Treatment: Conceptual Development

February 1987

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Prepared for:
U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
Edgewood Area, Aberdeen Proving Ground, Maryland 21010

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Prepared By:

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Metals contaminated soils are a problem at many US Army sites. In an effort to identify options for treatment of heavy metal contaminated soils and residues, the US Army Toxic & Hazardous Materials Agency (USATHAMA) initiated this study which is an evaluation of treatment technologies which may be candidates for further research and development. (over)		

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The first part of study involved the characterization of soil metal concentrations at the various sites and a review of applicable regulations guidelines/criteria for residual soil metal concentrations. These characterizations indicated that several Army installations had elevated total metal concentrations in their soils and Chromium, Cadmium and Lead were the most prevalent.

A detailed literature search resulted in the identification of 21 potentially viable treatment technologies. Process descriptions were prepared which included flow diagrams, and expected levels of performance. These process descriptions were subjected to a feasibility screening. This feasibility screening resulted in the following technologies being selected for further research and development:

- Microencapsulation
- Roasting
- Extraction ————— (keywords:)

Preliminary concept designs including process flow sheets, material balances and equipment sizing, were developed for each technology. In addition, total project costs were estimated for each technology. The three technologies were then subjected to a detailed technical evaluation. Based on this evaluation, WESTON recommends that a laboratory test plan be developed for Roasting. This plan will be written by WESTON as part of the final work element in this contract.



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EXECUTIVE SUMMARY

Over the past few decades, several U.S. Army installations have become contaminated with metals, solvents, and explosives. The Army established the Installation Restoration program in the early 1970's to address the problem of soils and groundwater contaminated with pollutants which could cause adverse environmental impact and restrict the use of the Army land. During the early stages of this program, it became evident that the scope of the restoration effort would be immense and many of the contaminants found at these sites were unique to the Army. As a result, the Army initiated a number of research and development projects to establish novel technologies for the treatment of contaminated soils.

The objective of this study is to identify the most promising metals contaminated soil treatment technologies for further development and implementation on U.S. Army installations. The study was performed by Roy F. Weston, Inc. (WESTON) for the U.S. Army Toxic and Hazardous Material Agency (USATHAMA) under contract number DAAK 11-85-D-0007, Task Order 7.

First, a review of the existing data on soil metal contamination levels was conducted in order to obtain a general characterization of the metals contaminated soil problem at Army installations. This review indicated that soils at many installations contain elevated levels of metals. Based on total metal analyses, Cr, Pb, and Cd may most often exceed EP toxicity limits. In addition, applicable regulations/guidelines were reviewed to establish target soil metal concentrations that the treatment technologies would have to meet or exceed. Based on this review, it was decided that EP toxicity levels should be achieved at a minimum. Lower treatment objectives may be set based on site-specific considerations and an assessment of potential impacts.

Next, an extensive literature search and personal contacts with researchers in the field were used to identify potentially viable metals contaminated soil treatment technologies. Twenty-one technologies were identified. Process descriptions were then developed for each of these technologies. These descriptions included blockflow diagrams, and a discussion of the technical feasibility criteria. The technologies were then subjected to a preliminary feasibility screening evaluation by a technical review committee.



The committee performed a comparative evaluation based on the following criteria: treatment effectiveness, long-term stability/performance, residual treatment/disposal requirements, flexibility, and material throughput rate. The results of this technical screening were conveyed to USATHAMA in a letter report dated 29 September 1986. This preliminary screening identified the following three technologies as the most attractive candidates for technology development:

1. Microencapsulation, which involves immobilizing the metals in the soil in a polymer matrix.
2. Roasting, wherein the metals are immobilized in a glassy matrix by heating the soil in a rotary kiln.
3. Extraction, which includes excavation and treatment with an appropriate extracting agent to remove the metals.

Following this preliminary screening, detailed concept designs, including flow sheets, major equipment sizing, material balances, estimated costs, etc., were developed for each of the above three technologies. These technologies were then subjected to a second-level detailed evaluation using numerous technical feasibility, development and implementation criteria and the estimated costs (in relation to that for conventional excavation and off-site disposal). The objective of this second-level evaluation was to determine which of the three technologies should be candidates for further research and development.

Roasting offers the potential for high performance, effective treatment through long-term immobilization of the metals in a glassy matrix, and cost-effectiveness at high throughput rates. The performance of extraction is less certain, as removal of metals in certain forms and certain types of soil may prove to be difficult. However, if development is successful, it also offers the potential for cost-effective decontamination of metals contaminated soil. While microencapsulation is expected to be effective for immobilization of metals, very high operating costs are anticipated.

Based on the results of the second-level evaluation, WESTON recommends that roasting be selected as a candidate for further research and development. A laboratory plan for bench-scale studies will be developed for this technology as part of the final work element under this task order.



1. INTRODUCTION

Over recent decades, parcels of Army real estate have become chemically contaminated. Explosives, solvents, and heavy metals were released to the soil as wastes associated with Army industrial operations. Activities that contributed to soil contamination included equipment rebuilding and repair, munitions manufacturing, and munitions disposal.

In the early 1970's, the Installation Restoration Program was established. One of its objectives was to solve the problem of soil that was contaminated to unacceptable levels that limited the use of the land by the Army. In addition, pollution of off-post soil and groundwater has occurred, as well as contamination of off-post drinking water.

During the course of the program, it became evident that many of the chemical contaminants at Army installations are either unique to or predominantly associated with the military. Acceptable limits for these soil contaminants often have not been established and have had to be determined on a site-specific basis through negotiation between the Army and appropriate regulatory agencies. Very few processes for removal, decomposition, or immobilization of the soil contaminants were available, and were not necessarily applicable to the Army's specific problems. Therefore, the U.S. Army initiated a number of research and development projects to establish novel technologies for the treatment of contaminated soils.

WESTON performed this study to identify the most promising metals contaminated soil treatment technologies for further development and implementation on U.S. Army installations for the U.S. Army Toxic and Hazardous Material Agency (USATHAMA) under contract number DAAK 11-85-D-0007, Task Order 7. A secondary objective is to determine the applicability of these technologies to metal bearing sludges and organic soil treatment residues.

The project began with the identification of the applicable regulations/guidelines which would determine the target levels that cleanup technologies would have to meet or exceed. Simultaneously, a characterization of the metal contaminated soils, sludges and soil treatment residues at U.S. Army installations was performed by reviewing available hard copy reports and utilizing the USATHAMA data base on soil metal contamination. Six sites were selected by USATHAMA as being representative of high soil metal concentrations found at U.S. Army installations across the country. The results of this site/waste characterization and regulations/guideline review are contained in Section 2.



Following this site/waste characterizaion effort, metal contaminated soil treatment technologies were identified and evaluated. Specific criteria and rating techniques were developed for the evaluation of the treatment technologies. This evaluation occurred in two stages. An extensive literature search was conducted through computerized data bases, journal reviews, and personal contacts with researchers in the field, resulting in the identification of 21 potentially viable technologies. Process descriptions were prepared for each of these technologies. These descriptions provided the basis for a preliminary screening evaluation conducted by a technical review committee. The outcome of this preliminary screening evaluation was the selection of three technologies for further study and evaluation. Section 3 contains the process descriptions for the 21 technologies. Section 4 contains a description of the preliminary screening process and its results.

Section 5 of this report contains more detailed concept designs for the three technologies selected for further evaluation. These designs include flow sheets, major equipment sizing, material balances, estimated project costs etc. which were used in the second-level, more detailed technical evaluation of the three technologies.

Section 6 of this report contains a description of the second-level evaluation process and its results. Section 7 contains the conclusions and WESTON's recommendations.



2. SITE/WASTE CHARACTERIZATION AND TREATMENT TECHNOLOGY DEVELOPMENT

2.1 Site waste characterization. WESTON first sought to identify the applicable regulations/guidelines which would determine minimum metal concentration targets or levels a treatment technology would have to meet. A survey was made of current Federal and state regulations (for states where the six IR sites referenced below are located). Telephone inquiries were made with Federal and state regulators. This work indicated that standards for metals concentrations in drinking water or for aquatic toxicity are available and may be applied in certain instances to groundwater remediation. However, fixed soil cleanup standards for metals do not currently exist. The government regulators expressed a preference for achieving the maximum cleanup to background metal concentrations. Recognizing that this is not always possible or cost-effective, cleanup levels are currently determined by site-specific assessments of the potential for migration and exposure.

In the absence of groundwater contamination or other indications of migration, metal concentrations in soil which result in its meeting the criteria for hazardous waste by the EPA Extraction Procedure (EP) Toxicity characteristics would require remedial action or permitting as a hazardous waste disposal facility. State and Federal regulators also indicated that the EP Toxicity limits would typically represent the minimum site soil cleanup requirement. Therefore, while lower standards may be set based on site conditions and assessment of potential impacts, EP Toxicity limits should be achieved at a minimum.

On 7 November 1986 [51 FR No. 216], EPA promulgated final regulations on the new Toxicity Characteristics Leaching Procedure (TCLP), which will also be used in determining if a given waste is hazardous. However, these regulations, which became effective on 8 November 1986, prescribed limits for solvents and dioxins only. For the present, the Extraction Procedure (EP) will be continued to be used in determining which wastes are hazardous due to the presence of metals (per 40 CFR 261.24).



Metal-contaminated soils, sludges, and soil treatment residues at the U.S. Army installations were characterized based on a review of existing hard copy reports on soil metal contamination data for all the sites. From this broad review, six sites with known metal contaminated soils were selected by USATHAMA to represent anticipated metals contaminated soil sites. Table 1 shows the range of metal concentrations in soils for the six selected sites. It must be noted that the data are for total metals only; there is little or no information on background or leachable levels. In the absence of EP toxicity data, the total metals analysis can be used as a rough indication of EP toxicity characteristics. By assuming that 100 percent of the metal content of the soil is extracted using the EP toxicity procedures, a "worst case" EP toxicity equivalent can be estimated. The EP toxicity test procedure calls for the total weight of solution to be adjusted, prior to analysis of the leachate for metals, so that the weight of liquid extract equals 20 times the weight of the original sample.

Thus, if the total metal concentrations exceed 20 times the EP toxicity limits for the extract, the sample could exceed EP toxicity limits under worst case assumptions. This provides a hypothetical guideline for assessing total metal concentration data for U.S. Army installations.

Table 2 shows a comparison of the actual soil metal concentrations and the hypothetical guideline criteria (20 x EP Toxicity limits).

Two waste streams which could potentially receive similar treatment for metals, electroplating sludge, and paint sludge were characterized. Table 3 shows the typical composition of an electroplating sludge and Table 4 shows the composition of an example paint sludge, based on previous studies conducted on actual Army installations. These data indicate that extrapolating sludge contains extremely high metals concentration, far in excess of that found in soils. Paint sludges also differ in characteristics as compared with soils, particularly with regard to moisture, pH, and the presence of organic solvents. Based on these site characterizations, it was concluded that:

- (a) Many installations have possible soil contamination problems based on total metals.
- (b) Cr, Pb, and Cd most often exceeded 20 x EP toxicity limit, which is presented as a hypothetical limit, for soils.
- (c) Limited data exists on mobility of metals in soils (i.e., EP Toxicity) at these installations.
- (d) Existing data (Letterkenney) indicated low mobility for soil tested.

TABLE 1. RANGE OF METALS CONCENTRATION IN SOILS FOR SIX SELECTED SITES
(TOTAL METALS, PPM)

Site	Cr		Hg		Pb		Cd		Ba		As		Se		Ag	
	Low	Hi	Low	Hi	Low	Hi	Low	Hi	Low	Hi	Low	Hi	Low	Hi	Low	Hi
Letterkenny	14	777			8.6	4,940	5.2	308	35	2,300	5.7	12.8				
TCAAP	7	146	0.1	2	3	3,000	1.5	31.3	6	3,800						
Annisston	1.2	3,000	0.00	23	1.16	956	0.05	453	0.49	343	2				5.58	
Riverbank	11	1,109			15	138					8	70		7		
Louisiana	9	41			9	89										
Tuoele		30									8	100				
20 x EP toxicity		100		4		100		20		2,000		100		20		100

Notes:

1. If all metals are extracted in the EP leachate, a 20 fold reduction in concentration occurs based on relative mass of sample and leachate.



TABLE 2. METALS OF CONCERN IN SOILS AT ARMY INSTALLATIONS
REVIEWED

	Metals exceeding hypothetical limit	Number of soil samples exceeding limit ¹
Total metals	Cr	47
>20 x EP Toxicity	Pb	13
limits ²	Cd	7
	Hg	1
	Ba	1
	As	1

¹Based on USATHAMA data base for six sites selected for
focused study.

²Assumes 100 percent transfer of metals from the soil to the
extract based on EP Toxicity test procedures.



TABLE 3. TYPICAL ELECTROPLATING SLUDGE COMPOSITION

Compound	Typical waste range (1,2) (dry wt., %)	Army representative waste (3,4) (dry wt., %)
Cu(OH)_2	0-15	7
Cr(OH)_3	0-15	10
Ni(OH)_2	0-60	7
Cd(OH)_2	0-1.5	1
Zn(OH)_2	0-30	7
Fe(OH)_2	0-40	7
CaSO_4	---	61
Overall % solids	15-35	---

Sources:

1. L.G. Tiwdwell, "Metal Value from Metal Hydroxide Sludges, Final Report," Hazardous Waste Engineering Research Laboratory, U.S. EPA, March 1986.
2. Unkn., Metal Finishing Journal, p. 238, August 1982.
3. M.T. Hepworth, "Plating Waste Sludge Metal Recovery, Report AMXTH-TE-TR-85015 for USATHAMA, Aberdeen Proving Ground, Maryland. 30 May 1985.
4. P.G. Chesler, "Plating Wastes Survey," Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia, Report No. MERADCM-2374, 77 pages, November 1982.



TABLE 4. EXAMPLE PAINT SLUDGE COMPOSITION¹

Compound	Water wash spray booth sludges	Alkaline paint stripper sludge	Organic paint stripper sludge	EP toxicity limits
<u>EP Toxicity (mg/l)</u>				
As	ND	---	---	5.0
Ba	0.05	---	---	100
Cd	ND	---	---	1.0
Cr	1.7	---	---	5.0
Pb	0.047	---	---	5.0
Hg	ND	---	---	0.2
Se	ND	---	---	1.0
Ag	ND	---	---	5.0
<u>Total metals (mg/kg)</u>				
Cr	---	120	1,200	---
Cd	---	67	130	---
Pb	---	6	400	---
pH	8.8	9.3	0.9	---
% solids	44.9	60.4	26.3	---
Specific gravity	1.26	1.4	1.4	---
COD mg/l	12,000	180,000	340,000	---
Fuel value (Btu/lb)	3,125	64	4,931	---

1. J.B. Hallowell, et al, "Chemical and Physical Characterization of Army Paint Wastes," USATHAMA, Aberdeen, Maryland, Contract DAAK11-84-C-0034, 24 October 1984.



- (e) Electroplating sludge has much higher metals content than soil.
- (f) Organic paint stripping sludge chemical properties (organic vs. aqueous) differ from soil.
- (g) The significant difference between soil properties and sludge waste properties makes it likely that numerous technologies may be applicable to one but not the other. Since the primary objective of the study is to develop technologies for metals contaminated soil treatment, it was concluded that technologies applicable to soils should be given emphasis over those solely applicable to sludges. A technology which can successfully treat soil but not sludges should not be eliminated on this basis alone.

2.2 Treatment technology development. WESTON then investigated current research on treatment of heavy metal contaminated soils. These investigations included computerized literature searches of various data bases, journal and report reviews, and personal contacts with researchers in the field. The following computerized data bases were accessed to obtain information:

- (a) NTIS
- (b) Enviroline
- (c) Pollution Abstracts
- (d) Conference Papers Index
- (e) Engineering Meetings
- (f) Metadex

These data bases were searched using the following general keywords:

- (a) Heavy metals.
- (b) In-situ treatment.
- (c) Metals removal-water.
- (d) Paint sludge.
- (e) Metals recovery.
- (f) Plating sludge.

Following these initial searches, these data bases were again accessed using key words specific to the selected technologies. In addition to these computerized searches, personal contacts were initiated with the following people/organizations:

- (a) EPA Research Project Officers
- (b) DOD Research Project Officers
- (c) University Researchers
- (d) Commercial Enterprises



These people/organizations were identified through EPA and DOD research program reviews, publicity brochures, review articles, and personal contacts with EPA and DOD officials.

This investigation culminated in the identification of 21 potentially viable treatment technologies. Technologies identified for treatment of metals contaminated soils or sludges could be categorized by type of process and approach to metals treatment as follows:

Type of Process

- (a) Thermal.
- (b) Chemical.
- (c) Electrochemical.
- (d) Biological.
- (e) Physical.

Approach

- (a) Immobilization.
- (b) Mobilization.
- (c) Isolation.
- (d) Direct Recovery.

These technologies were then subjected to a two-stage evaluation to select the best candidate technologies for research and development. The first stage evaluation was designed to screen the technologies based on a limited number of criteria to select two to three of the best technologies for further evaluation. The second stage evaluation included a further development of the conceptual designs, cost estimation, and a wider range of criteria.

Process descriptions on each of the metal treatment technologies were first developed to perform this preliminary evaluation. These process descriptions, presented in Section 3, were designed to facilitate the preliminary evaluation and to be consistent with the evaluation format. The process descriptions are organized as follows:

(a) Description

- Theory.
- Level of development.
- Available performance data.
- Conceptual design schematic.

(b) Treatment effectiveness

Actual or expected performance based on results available in the literature and/or engineering judgement. The treatment goal is to render the soils capable of passing the EP Toxicity test for disposal as nonhazardous materials.

(c) Long-term stability/performance

Based on literature and/or engineering judgement, determine if treatment performance is likely to have permanent, long-term effectiveness in rendering the soil nonhazardous.

(d) Residuals treatment/disposal requirements

Identification of potential residual waste side streams (i.e., extract solutions) that will require further treatment and/or disposal due to expected hazardous properties.

(e) Flexibility

Ability to treat various soil/site types, other waste streams (i.e., sludges), to treat for organic compounds concurrently with metals, or be readily linked to other processes for organic or explosive compound treatment.

(f) Material throughput rate

Actual throughput rates or anticipated ability to scale up.

(g) Potential disqualifiers

Identify known or potential "fatal flaws" which can hinder development and implementation, including:

- Inherently unsafe.
- Uncontrollable environmental risk of mobilization.
- Uncontrollable air emissions.
- Exceedingly expensive.
- Exceedingly complex materials handling, operation, or maintenance.

Following the presentation of process descriptions in Section 3, the preliminary screening process and the results of the screening are presented in Section 4.

3. PROCESS DESCRIPTIONS

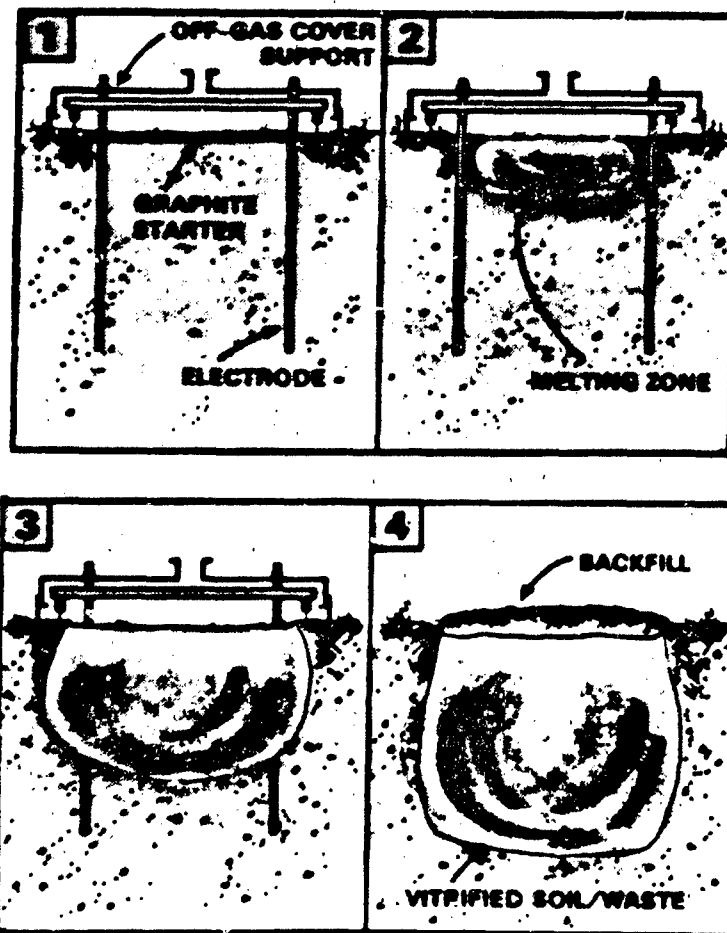
3.1. In situ vitrification.

3.1.1 Description. In situ vitrification (ISV) is a process of immobilizing the contaminants in soil by converting the soil into a stable glass and crystalline form that has chemical durability properties similar to that of granite. This is an emerging technology which has been extensively tested and developed by the Battelle Pacific Northwest Laboratory (under contract to the U.S. DOE) on soils contaminated with radioactive materials. Battelle's scientists claim that while the technology "is not a panacea for all contaminated soils," it does have the following advantages:

- (a) Long-term stabilization of radioactivity (>10,000 years).
- (b) Cost-effectiveness (\$160 to \$330/m³).
- (c) Applicability to varying soil and site conditions.
- (d) Minimal occupational exposure to the waste during processing.
- (e) Low-energy requirements (<1kw/kg).

The ISV process is initiated by first inserting molybdenum or graphite electrodes into the soil in a square grid pattern. The spacing of the electrodes varies with the size of the ISV unit (e.g., 0.23 to 0.36 meters for an engineering unit, 3.5 to 5.5m for a large scale unit). Next a conductive mixture of flaked graphite and glass frit is placed in an X pattern among the electrodes in 5 cm deep trenches on the soil surface to initiate electrical conductance. Voltage is then applied to the electrodes via a power source (as much as 4,160v for the large-scale unit). The graphite mixture is quickly heated to soil-melting temperature (1,100 to 1,600°C). As the surrounding soil melts, it becomes electrically conductive. The graphite is eventually consumed by oxidation and the molten soil maintains the electric conductivity.^{1,2}

The molten soil zone grows outwards and downwards as the process progresses and eventually encompasses the volume between the four electrodes (see Figure 1). The temperatures in the molten zone approach 2,000°C and organic wastes in the soil are pyrolyzed. The resultant gases from the process burn when they come into contact with the air. The high temperatures and long residence times result in essentially complete combustion and/or destruction of the organic components. Most of the nonvolatile and semivolatile elements at these temperatures such as heavy metals, remain in the molten glass and become



Source: Reference 1

FIGURE 1 Process sequence of in situ vitrification.



part of the glass and crystalline product after cooling. A small percentage of the hazardous elements that may escape are collected by an off-gas hood that is placed over the vitrified zone. This gas is then treated in an off-gas treatment system housed in a mobile unit. Thus, the process is self-contained and transportable (see Figure 2).

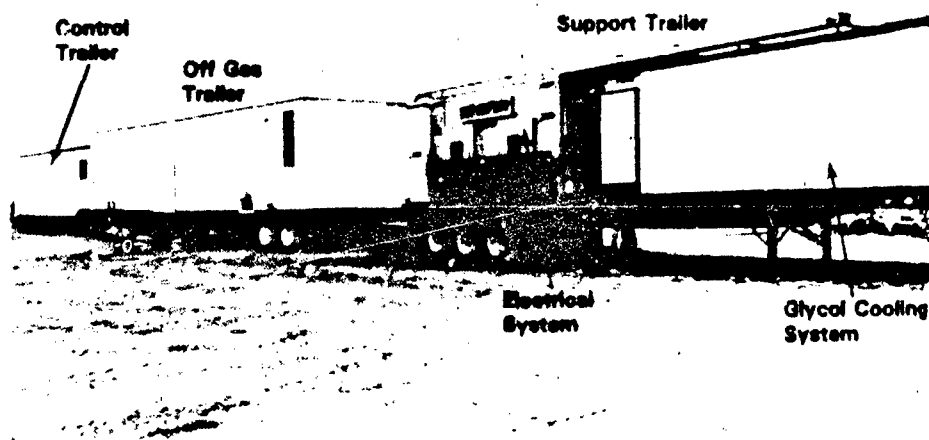
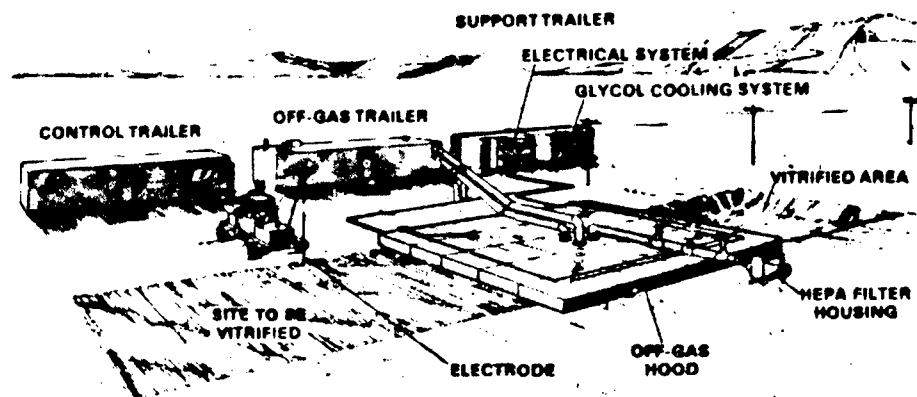
When the desired vitrification depth is attained, voltage to the electrodes is discontinued and the molten mass is allowed to cool. The entire cooling process can take several months, depending on the size of the vitreous mass produced, but this does not interfere with the use of the power system and off-gas treatment for additional settings. After the surface of the molten glass is cooled, the vitreous mass is backfilled with clean fill due to a reduction in volume upon treatment.

3.1.2 Treatment effectiveness. Literature indicates that the effectiveness of the ISV process has been demonstrated over a range of site sizes. As indicated previously, most of these tests have been done on radioactive contaminated soils where concern for mobility is more acute than for metals. The leachability of metals following vitrification is expected to be negligible.

Recently four large-scale tests (300-500 metric ton blocks) have been completed in the initial phase of operational acceptance testing of the large scale equipment. All test data appear to show that the technology can be used on different types of soils. Soil moisture content would have an effect on the amount of power that has to be supplied to accomplish the vitrification due to its high heat of vaporization.

Electrode spacings for a large scale unit vary from 3.5m-5.5m; the molten zone would encompass the area between all the four electrodes. Depths of the zone vary from 2m to 13m. Metal objects such as pipes and bars can short-out opposing pairs of electrodes preventing heat from being dissipated into the melt. However, test results show that the ISV process can accommodate metal objects occupying up to 70 percent of the spacing between the electrodes.

3.1.3 Long-term stability/performance. Once glassification is achieved, the amorphous glass product of ISV treatment is a low permeability - low metals mobility matrix which is thought to be extremely stable over time (>10,000 years). Geologic stresses are expected to cause fractures such as those which occur in bedrock, which would cause secondary hydraulic permeability. The low metals mobility and low fracture surface areas should provide relatively permanent treatment effectiveness.



Source: Reference 1

FIGURE 2 Large-scale testing unit.



3.1.4 Residuals treatment/disposal requirements. One of the inherent advantages of the ISV process is that there is no hazardous residual to be disposed. The gaseous effluent can be treated in a mobile off-gas treatment unit. The vitrified soil remains in place. Land reclamation and reuse may be limited by the physical properties (hardness, low permeability).

3.1.5 Flexibility. Though most of the testing has been confined to radioactive contaminated soil, there is some information on organic contaminated soils. The conclusions from these tests were:^{1,2}

- (a) Burial depth attenuates release of hazardous elements (e.g., a meter of uncontaminated overburden lowers release fractions significantly).
- (b) Gaseous releases associated with combustibles result in significantly higher release fractions.
- (c) Organics are pyrolyzed in the soil melting process at high temperatures, resulting in essentially complete combustion in the hood directly above the molten zone.

Communications with Battelle indicated that the process can also be adapted to sludges or other waste materials either in situ (if waste is in-ground or in above-ground process equipment [see on-site vitrification]). While it could be used on residues from organics treatment processes, it can be used alone to treat for both organics and metals.

3.1.6 Material throughput rate. ISV has been demonstrated in field tests treating a soil cube approximately 20 feet on each end. The process requires 2 to 3 days to complete. Thus, throughput rate for this transportable system is 100 to 150 cubic yards per day. Higher rates would require multiple units operating on the site.

3.1.7 Potential disqualifiers. Safety may be a concern due to the use of high voltage power and the release of volatile organics and inorganics to the air. Air emission controls are included in process design. Based on testing and projections, problems of safety, release to the environment and air emissions are controllable. Special gas treatment may be required for emission of certain hazardous substances.



3.1.8 References.

1. Buelt, J.L., V.F. Fitzpatrick, and C.L. Timmerman, Chemical Engineering Progress, pp. 43-48, March 1985.
2. Assessment of Innovative Technologies for Hazardous Waste Uncontrolled Sites for Office of Technology Assessment, U.S. Congress by E.J. Martin, TTEEMD, Inc., Derwood, Maryland 20855, January 1985.
3. Letter from C.L. Timmerman, Senior Research Engineer, Battelle Pacific Northwest Laboratories to Peter Pugliesi, Roy F. Weston, Inc., 19 May 1986.
4. Sanning, D.E., "Contaminated Land-Reclamation and Treatment." Edited by M.A. Smith, Plenum Press, New York and London, 1985.
5. U.S. Patent 4,376,598 held by the U.S. Department of Energy.

3.2 On-site vitrification.

3.2.1 Description. Conventional glass-making techniques have been adapted in this process to pyrolyze and oxidize or fuse wastes with molten glass to form a residue which is nonleachable. Soils containing glass minerals may be readily vitrified with minor additions of glassifying agents. There are two firms who are developing or marketing this process. They are:

- (a) Battelle Northwest-Joule-Heated Glass Melter.
- (b) Penberthy Electromelt International-Electromelt Pyro-Converter.™

The process was initially studied for long-term isolation of radioactive wastes and is now being applied to hazardous wastes and site remediation.

Battelle's process utilizes the material being heated as the resistance element in an electrical circuit without transferring heat from a metallic resistance element. Contaminated soils may be accepted directly with little or no pretreatment. Organic constituents would be destroyed by pyrolysis and/or combusted at the operating temperature of 1,200°C (2,200°F) while inorganic constituents (including nonvolatile heavy metals) would react with glass formers to create an impermeable

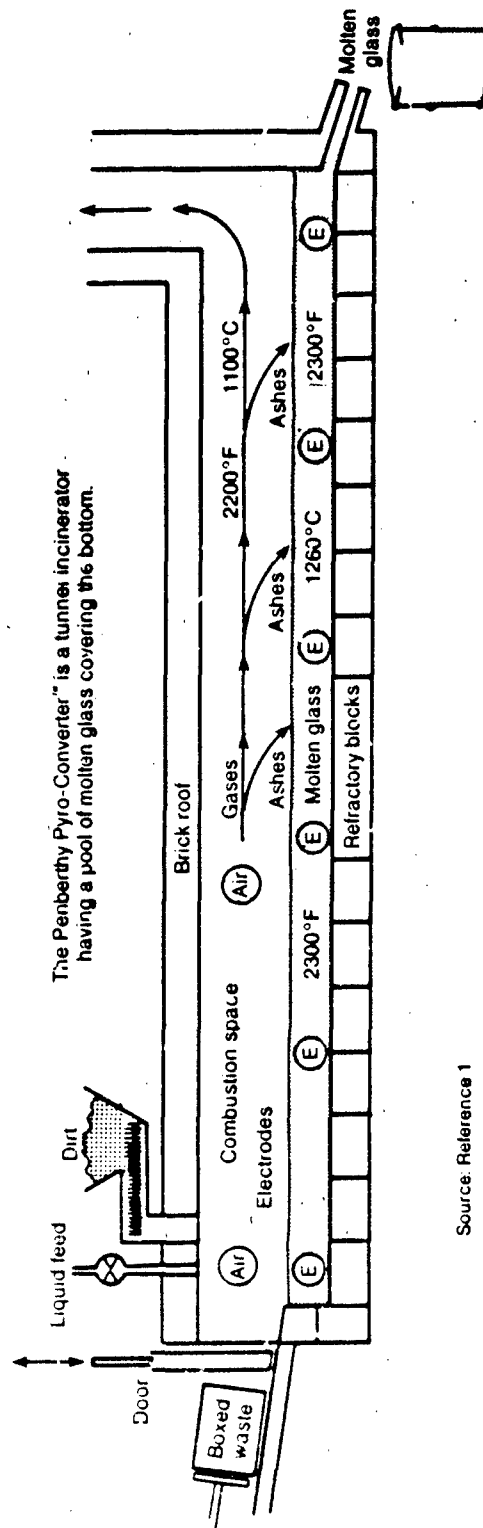


glass matrix. Molten glass from the melter is continuously drained into an inexpensive receiving canister and cooled to ambient temperature. These canisters may be disposed of in a non-secure landfill. Battelle claims that the glass residue is in itself a long-term disposal medium exhibiting leaching properties similar to Pyrex or granite. Off gases from the melter may include pyrolysis products from organics and volatile inorganics which may require additional treatment. Organic pyrolysis gases combust upon leaving the melt when provided adequate oxygen.

In Penberthy's process, waste is directly charged into a pool of molten glass also heated in an electric furnace. Again, this results in the organic constituents being destroyed by pyrolysis and pyrolysis gas combustion while the inorganic constituents mix with the molten glass to form a nonleachable residue. The residue is drained into canisters for disposal in a non-secure landfill. This process has been successfully tested using a number of wastes. The company has one pilot-scale unit at Seattle, Washington and another experimental unit at a Monsanto facility in Ohio (used to process transuranic wastes). Numerous alternative configurations are offered in sales literature, including a rotary kiln primary treatment step followed by the standard furnace with molten glass at the base to "capture dust particles" and provide secondary combustion. Options described for air emission control include limestone rock packed tower, wet scrubbing, and mist elimination. The entire system is maintained under negative pressure by means of an exhaust blower. Figure 3 shows a schematic diagram of the basic process.

Battelle's process is still at an early developmental stage. However, the Penberthy process has been tested on organic wastes and has proved to be successful. Penberthy is in a good position to commercialize this process based on these pilot-scale test results and their extensive experience in glass making equipment.

3.2.2 Treatment effectiveness. The vitrification process has been shown in studies on in-situ vitrification to produce an extremely stable, nonleachable product which can be placed in a non-secure landfill. No data on metals leachability is available from specific publications on on-site vitrification studies, but work on in-situ vitrification is directly transferable.



The Penberthy Pyro-Converter" is a tunnel incinerator having a pool of molten glass covering the bottom.

Source: Reference 1

FIGURE 3 Penberthy Pyro-Converter.



3.2.3 Long term stability/performance. The glassy residue that is formed contains the inorganic constituents (including heavy metals) and is very stable. Leaching characteristics of this glassy residue are similar to that of Pyrex and granite. It will be stable under all anticipated environmental conditions. Therefore, this residue can be safely disposed as non-hazardous fill and not present long-term risk or liability.

3.2.4 Residuals treatment/disposal requirements. The glassy residue may be disposed or backfilled with no special precautions. In some cases, beneficial reuse may be possible. Off gas from the process will require treatment. This is especially critical for instances where volatile metals (e.g., mercury, arsenic) or chlorinated organics are present in the waste. Additives to reduce volatilization, as discussed for the "roasting" technology, have not been explored. After cooling, metals may be collected as dust and recycled to the melt if the fraction remaining in the melt is high enough. Hydrochloric acid from chlorinated organic oxidation may require recovery or treatment.

3.2.5 Flexibility. The ability of this process to handle organic wastes in combination with metals has been demonstrated. No pretreatment for organics destruction would be required. The system can also readily handle liquid wastes and sludges. In these cases, the addition of glass-forming raw materials will be necessary. The equipment is small enough to be installed on the site where waste is being generated, eliminating the need to transport solid or liquid wastes.

3.2.6 Material throughput rate. While the Battelle process remains developmental, Penberthy equipment is reportedly available to process up to 4,000 lb/hr or 48 tons/day. Penberthy promotional literature indicates that units could be sized to process up to 25,000 lb/hr or 300 tons/day.⁴



3.2.7 Potential disqualifiers. The costs associated with the application of this process to the treatment of metals contaminated soils appear to be somewhat high. Penberthy estimates that for a 2,000 lb/hr feed of tetrachlorobenzene or similar substance the capital costs would be \$1 million and operating cost would be \$100/ton of feed. It must be noted that this estimate is based on organic waste which is readily combustible. It may be significantly higher for soils contaminated with heavy metals.

This process also involves the excavation of the contaminated soil and its associated cost. Since the process yields a reduced volume of vitrified wastes which have to be disposed either on-site or off-site (another cost increasing factor), the excavated area would have to be partially or fully backfilled with fresh soil. Additionally, off-gas treatment may be expensive especially in instances where volatile metals are present in the soil. The potential technical problems all appear to be manageable, however.

3.2.8 References.

1. Innovative Thermal Hazardous Waste Treatment Processes by Harry Freeman, Hazardous Waste Engineering Research Laboratory, U.S. EPA, Cincinnati, Ohio 45268 (undated).
2. Personal communication with Dennis Hotaling, Technical Manager, Penberthy Electromelt International, Seattle, Washington 98108, 24 July 1986.
3. Penberthy, Larry, "Penberthy Pyro-Converter Detoxifies Hazardous Materials," Hazardous Materials and Waste Management, p 14, January-February 1986.
4. Penberthy Pyro-Converter, Sales Literature (8m-3-84).
5. Personal Communication with Bill Bonner, Battelle, Pacific Northwest Laboratories, Richland, Washington, 5 May 1986.



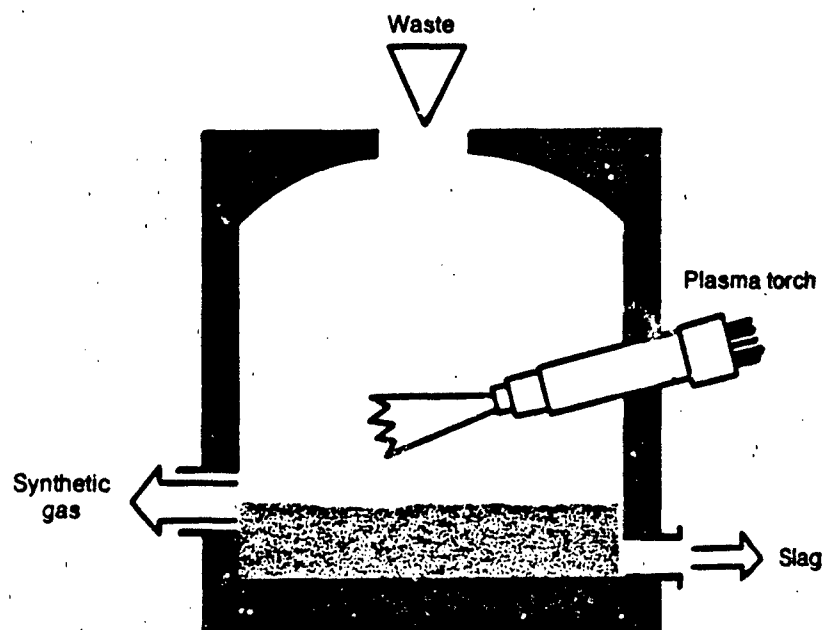
3.3 On-site plasma arc (metals recovery).

3.3.1 Description. This technology has been applied on an experimental or pilot basis to address metallurgical process applications. Most of the research and development has been confined to metals smelting/melting, ore roasting, metals calcining, chemical reactions/synthesis and high temperature gas heating. The impetus for these efforts in the late seventies and early eighties was the high cost of hydrocarbon fuels. The aim was to develop alternative energy-efficient technologies which use electricity. Some studies have been conducted on waste materials, primarily PCBs.

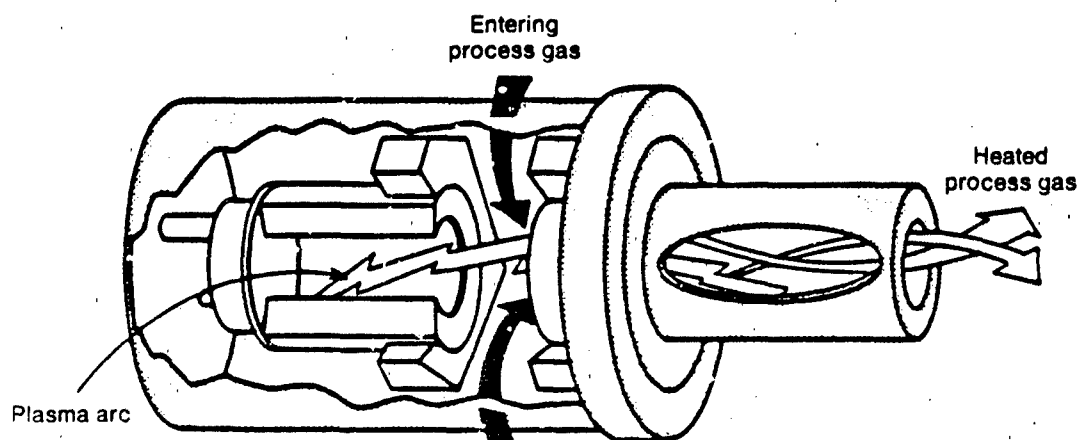
There are a few different types of plasma arc systems under investigation. The heart of all these systems is the plasma arc device (or torch). This consists of a closely-spaced pair of electrodes installed in a furnace which produce an electrical arc. A process gas is injected into the gap between the electrodes. This gas can be an inert, oxidizing or a reducing substance. The gas in and around the arc is activated into an ionized atomic state absorbing large quantities of energy and losing electrons. The resulting gas is known as the plasma state (fourth state of matter) consisting of charged and neutral particles with an overall charge near zero and with electron temperatures up to 28,000°C (50,000°F).^{1,2} As the molecules or atoms relax from their highly activated state to lower energy levels, ultraviolet radiation is emitted.

Wastes are introduced into the reactive zone of the furnace where the molecular bonds of the waste material are broken due to the bombardment by electrons and high intensity ultraviolet radiation. This results in the conversion of the waste materials to basic elements (e.g., carbon, hydrogen, oxygen) or simple molecules (i.e., CO). The activated components of the plasma decay when their energy is transferred to the waste material. Hazardous gases which may emanate from the furnace must be scrubbed. Figures 4 and 5 show various configurations of plasma arc reactors and furnaces.

Performance data which are currently available are mainly for liquid wastes. The system has recently been tested for destruction of PCBs. There is very limited information on treatment of soils contaminated with metals. However, the fact that the system has been used in recovery of metals from low grade ores indicates that it may be used in certain instances for metals recovery from highly contaminated soils. In the treatment of ores, it is used as a heat source for smelting or primary reduction (i.e., to replace conventional blast furnaces). This process, when applied to soils with a mixture of metals, will probably result in a liquid melt being formed, rather than oxidative destruction, as occurs with PCB's.

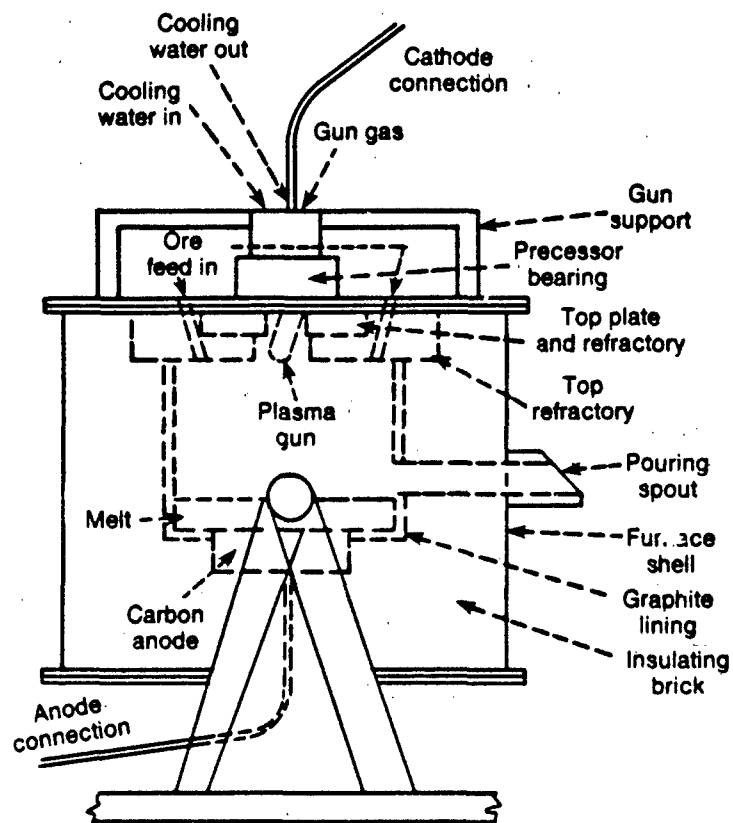


Source: Reference 3



Source: Reference 4

FIGURE 4 Plasma arc reactor schematic.



Source: Reference 5

FIGURE 5 Cross section of plasma arc furnace.

3.3.2 Treatment effectiveness. The literature indicates that no full-scale performance data exists for waste materials. Experimental data indicate that the system was effective in the destruction of PCB wastes.

The work completed for metallurgical applications indicates that metals recovery is possible for high concentration wastes. Success in processing ores indicates that soils can be readily handled by the equipment. The high silica and mineral content may affect operation and separation of metals. Based on the high operating temperatures, the formation of a vitrified residue is likely. This residue may provide a non-leachable matrix for safe disposal. The high temperatures may, however, result in a high level of metals in the off-gases passing onto the dust collectors. This dust may require disposal as a hazardous residue. No data are available for metals contaminated soils at this time.

3.3.3 Long-term stability/performance. Since the process essentially converts the waste components to basic elements, destruction of the organic waste is total. Therefore, any treated soil would be free of organic contaminants. Long-term performance for metals depends on the results from soil processing. If, for example, metals are recovered or trapped in a vitreous matrix, long-term stability is assured.

3.3.4 Residuals treatment/disposal requirements. After the contaminants have been removed from the soils, the residual slag would have to be disposed. Slag leaching properties are as yet undetermined. Hazardous gases that may be generated from the furnace would have to be treated using scrubbers. Metal containing dusts may be recovered and could require landfill disposal or further treatment.

3.3.5 Flexibility. Tests have clearly shown that the process can be used to treat organic wastes. Soils contaminated with organics may be successfully treated by the process. Sludges and other waste materials may also be treated.

3.3.6 Material throughput rate. Tests have been conducted for wastes in a pilot unit sized for 500 lb/hr of sludge². Based on metallurgical studies and applications, scaleup should be achievable.

3.3.7 Potential disqualifiers. Energy cost is an important factor in determining the economic feasibility of the process. Plasma arc has been attractive in metallurgical applications only where poor heat utilization and high cost occur for fossil fuels as compared with electricity applied via plasma arc. In recent years the cost advantage for electricity has disappeared and interest in plasma arc has also declined. Literature indicates that the capital and operating costs (based on a pilot-scale test) will be high.

Additionally, hazardous gases emanating from the process will require treatment. Lastly, the application of the process to recover metals is limited by economics to situations where large soil areas are highly contaminated with metals.

3.3.8 References.

1. "Assessment of Innovative Cleanup Technologies for Hazardous Waste Uncontrolled Sites." Study done for the Office of Technology Assessment, U.S. Congress by E.J. Martin, Ph.D., P.E., TTEMD, Inc., Derwood, Maryland 20855, January 1985.
2. "Innovative Thermal Hazardous Waste Treatment Processes," by Harry Freeman, Hazardous Waste Engineering Research Laboratory, U.S. EPA, Cincinnati, Ohio 45268.
3. Kiang, Y.H. and A.A. Metry, Hazardous Waste Processing Technology, Ann Arbor Science Publishers, Inc., 1982.
4. Chemical Engineering, 5 September 1983.
5. Savage, P.R., Chemical Engineering, V. 86, No. 4, 26 February 1979, p. 75.

3.4 High temperature fluid wall (HTFW) reactor.

3.4.1 Description. This process has been developed and patented by J.M. Huber Corporation, Borger, Texas. It utilizes radiative heat to pyrolyze the waste components forming elements or simple compounds. At the heart of the HTFW reactor is a cylindrical porous graphite "core" through which waste material flows. The annular space between the inner cylinder and another outer cylinder contains the carbon electrodes. These electrodes, operated at temperatures of 4,200 to 4,300°F, are heated electrically. The electrodes in turn heat the graphite core to incandescence at a temperature of 4,100°F.



Waste materials are gravity fed into the core from the top of the reactor. A constant flow of nitrogen through the annulus and porous core results in a fluid barrier being formed between the waste materials and the core (hence the name "fluid wall" reactor). Various other inert gases like argon may be used to act as a fluid wall. Elimination of contact between the waste materials and the core reduces maintenance problems such as fouling. Solids must be reduced in size to 10 mesh or smaller and dried prior to processing.

Unlike combustion processes, the waste materials are heated by radiation rather than convection or conduction and can be processed in the absence of oxygen. The company estimates that the radiant power density is approximately 1,200 w/sq. inch. The waste materials are very rapidly heated at 10^3 - 10^7 °F/sec. Organic wastes are pyrolyzed at these temperatures resulting in their conversion into basic elements or simple molecules that reside in the gaseous phase. Inorganic wastes or residues including heavy metals, are vitrified along with clay and other minerals in the soil to form glassy, granular materials. This vitrified material is non-hazardous and can be disposed at a non-hazardous landfill.

There are additional reacting chambers following the HTFW reactor where the gaseous phase is maintained at high temperature for further reaction and then cooled. After cooling, the granular vitrified solids drop into a sealed container for disposal or backfilling. Subsequently, the gases are sent through a baghouse for particulate removal, followed by a scrubber for chlorine removal and finally through an activated carbon column which acts as a back-up chlorine and organics removal device. Scrubbing and activated carbon gas treatment steps are necessary for chlorinated hydrocarbon processing only. Figures 6 and 7 show sections of a HTFW reactor.

Huber presently has a stationary pilot unit with a 12-inch core diameter and a transportable unit with a 3-inch core diameter. The maximum feasible size of a transportable unit was estimated to be 18 to 27 million kg per year 20,000 to 30,000 tons/year).

J. M. Huber Corporation has estimated that for a large site (>100,000 tons of material) the cost per ton would be in the range of \$365 to \$565. The breakdown of this cost is as follows: maintenance - 12 percent, labor - 7 percent, energy - 29 percent, depreciation - 18 percent, other (including permitting) - 34 percent.

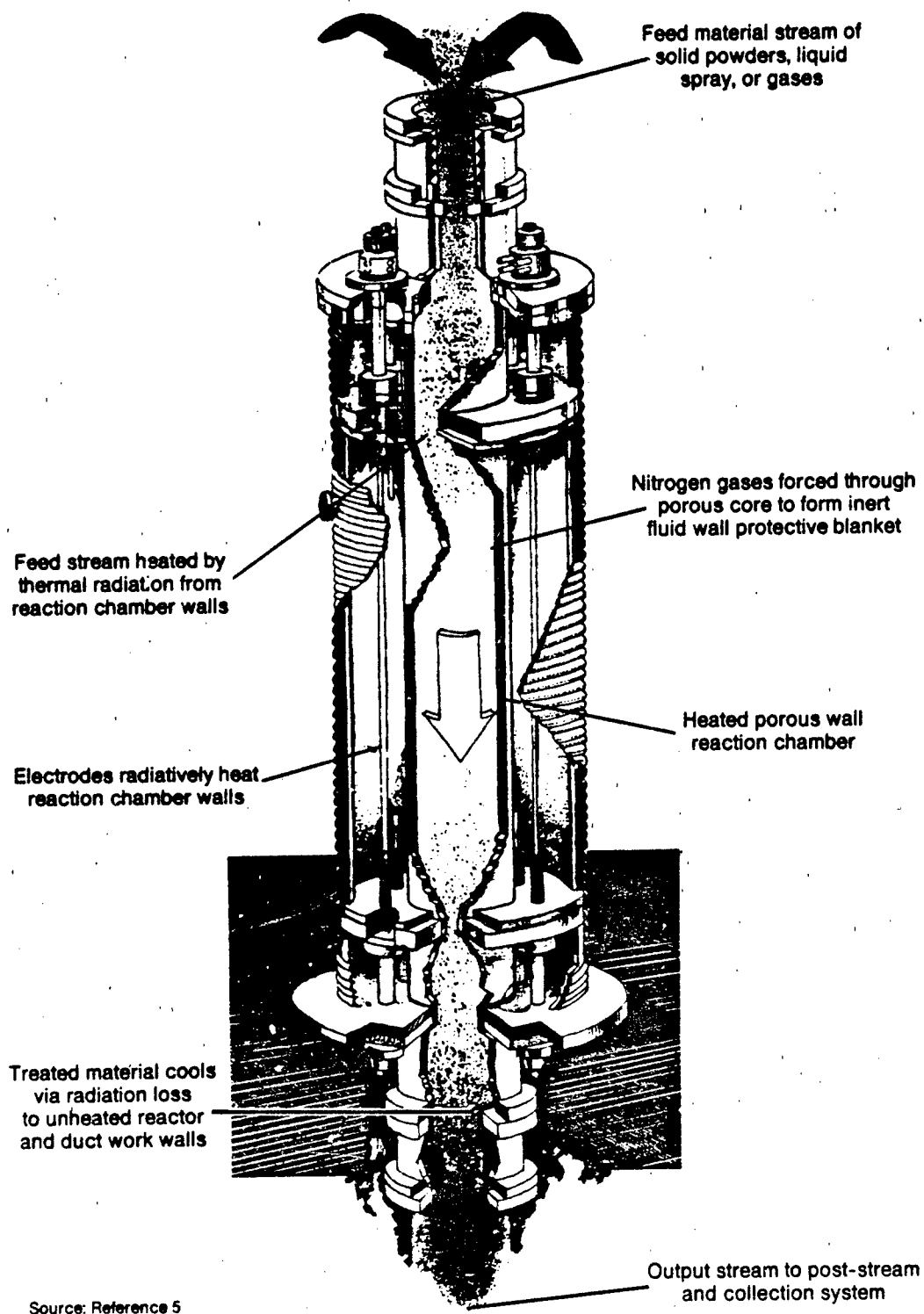
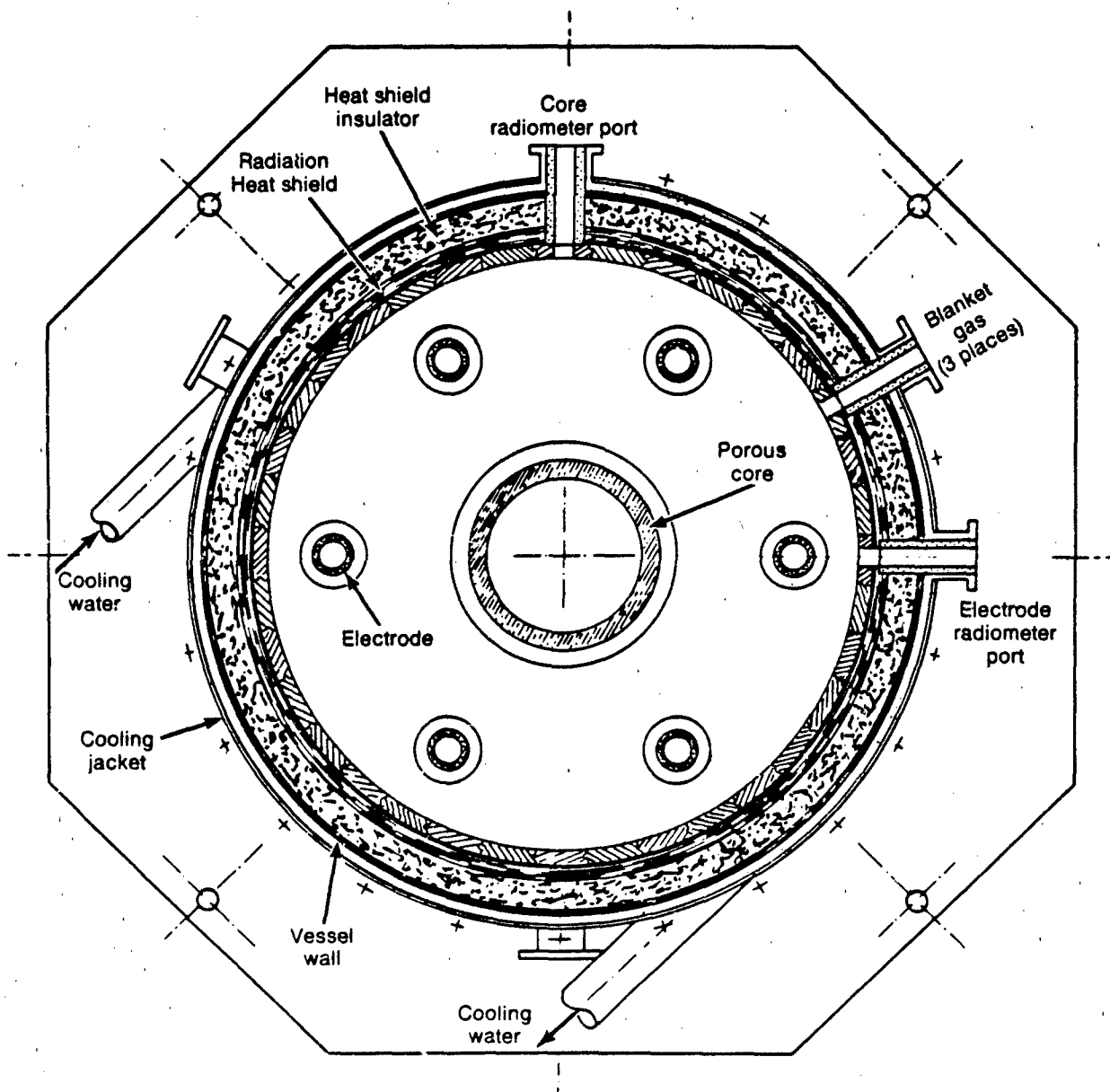


FIGURE 6 Vertical cross section of a high temperature fluid wall reactor.



Source: Reference 5

FIGURE 7 Horizontal cross section of a high-temperature fluid wall reactor.



3.4.2 Treatment effectiveness. The available literature shows that the process has been successfully utilized in the destruction of PCBs and dioxins in contaminated soil. These tests were performed at the experimental and pilot-levels. Due to the high temperature in the reactor, very high destruction efficiencies are achieved since destruction is by pyrolysis. Since the reactor operates in an inert atmosphere, no oxygen containing by-products like dioxin are formed. In a personal communication with Mr. Jim Boyd of the Huber Technology Group,² it was learned that the company has done some work studying the fate of metals. This work has not yet been published because it was done under contract to the U.S. Air Force. The company did not specifically design the process to remove or treat for metals but examined the fate of metals while evaluating its ability to destroy organics. Preliminary indications are that metals with lower melting points like Pb and Zn are vaporized, recondensed and captured in the baghouse. The remaining heavy metals end up in the vitrified phase which is thought to have a low leachability. Test data show a reduction in leachability of some metals but no data are available to confirm this for high feed metals concentrations.

3.4.3 Long-term stability/performance. The process results in the effective treatment of organic wastes and volatilization/condensation of certain metals from contaminated soil. The remaining inorganic waste materials end up in a granular glassy form. This glassy material is thought to be non-hazardous and very stable. Once formed into a nonleachable matrix, metals will not be leached out of this vitrified material under most conceivable long-term environmental conditions.

3.4.4 Residuals treatment/disposal requirements. For metals contaminated soils, the vitrified (glassy) granular material containing the metals will require disposal. It is thought that this material will be nonhazardous and very stable but this has not been confirmed for waste streams with high metals concentrations. If this material is nonhazardous, disposal or backfilling can be accomplished at low cost and low future risk.

The gases from the reactor must typically be treated prior to their being released to the atmosphere. If the phenomenon of vaporizing and subsequent recondensation of low-melting point metals is confirmed, then disposal of bag-house dust as a hazardous waste may be necessary. The effectiveness of the potential for dust recycle to the feed has not been addressed.



3.4.5 Flexibility. Several demonstrations have shown that the process can be used to treat soils contaminated with organics. Recent work has shown that soils contaminated with low levels of metals can be treated using this process without producing a hazardous vitrified residue.

Sludges and other residues may be similarly treated if dried, reduced in size, and free flowing before input to the reactor.

3.4.6 Material throughput rate. Test or commercial units are available to process 25 to 50 tons/day.

3.4.7 Potential disqualifiers.

- (a) High energy requirements.
- (b) Disposal problems with baghouse dust.
- (c) Hazardous gases may have to be treated.
- (d) Particle size of feed is critical.

3.4.8 References

1. Lee, K.W., W.R. Schofield, and D.S. Lewis, Chemical Engineering, 2 April 1984, pp 46-47.
2. Personal communication with Mr. Jim Boyd, J.M. Huber Corporation, 21 July 1986.
3. Assessment of Innovative Clean-up Technologies for Hazardous Waste Uncontrolled Sites for Office of Technology Assessment, U. S. Congress by E.J. Martin, TTEMD, Inc., Derwood, Maryland 20855, January 1985.
4. Innovative Thermal Hazardous Waste Treatment Processes by Harry Freeman, Hazardous Waste Engineering Research Laboratory, U.S. EPA, Ohio 45268 (Undated).
5. "Huber Technology Fluid Wall (HTFW) Reactor," J.M. Huber Corporation, Borger, Texas, 1983.

3.5 Roasting.

3.5.1 Description. Most of the work in this area has been performed in Japan. As a result, there is limited information which is readily accessible, on process performance. Reporting on the Japanese work focuses on treatment of heavy metal contaminated dust or wastes.



The basic principle of this process is immobilization of the heavy metals in a vitrified form. As the waste material is heated it passes through the following stages:

- (a) Evaporation of the residual water.
- (b) Decomposition of hydroxides and salts to form the corresponding oxides.
- (c) Sintering, which is the fusing together of solid particles without reaching the liquid state, occurs at about two-thirds of the melting temperatures ($^{\circ}\text{K}$).
- (d) Melting of heavy metal oxides (around $2,000^{\circ}\text{C}$).

This process heats the waste to sintering temperatures where heavy metals are immobilized in the slag. X-ray diffraction photographs of the sintered slag show that the metals are in the dispersed phase while the silica melts to form the continuous phase. Since immobilization is the purpose behind this process, volatilization of metals should be prevented as far as possible. To achieve this, silicates in the form of clay minerals (i.e., kaolinite) sodium hydroxide and ferric oxide may be added to the melt if not present in the waste or soils. This yields a more viscous melt and the boiling point of the metal compounds in the melt is raised. Roasting of contaminated soils has not been studied, but naturally occurring silica in soil may provide the same benefit for soil treatment.

While there has been research conducted in Japan there is no information to indicate that full scale operations have been conducted. The probable furnaces would be either the rotary-kiln or the Flammenkammer (FLK) oven. Both these designs are capable of handling the molten slag. There is some experimental data on the effect of additives and processing temperature on the leachability of slag derived from simulated metal hydroxide (electroplating) sludge. It has been shown that leachability decreases with increasing amounts of additives like kaolinite ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 24\text{H}_2\text{O}$) and increasing processing temperature. Organic waste components would be readily destroyed by combustion at the operating temperatures required.

3.5.2 Treatment effectiveness. There is no information on full-scale operations on soils contaminated with heavy metals. However, experimental data are available for simulated metal hydroxide sludge which seem to indicate that the metals are immobilized in a vitrified form and the glassy residue has very low leachability.



An appropriate mixture of additives (up to a 1:1 ratio), and temperatures from 1,000°C to 1,200°C (1,800°F to 2,200°F) were effective in reducing chromium levels below 1 mg/L in both boiling water and weak acid (pH 5; H₂SO₄) extractions. These extractions were apparently conducted to result in a 50:1 weight ratio of extract to treated waste in contrast to the 20:1 ratio for the EP Toxicity Test (pH5; acetic acid). These results indicate that leaching is limited to the surface of the slag and that EP toxicity targets can be achieved even for high concentration (15 to 100 percent) chromium hydroxide sludges.

While no experimental data is available for soils, the natural mineral content and lower anticipated metals concentrations should make most soils a good potential substrate for treatment. Results are also not available in the reference for other hazardous metals.

3.5.3 Long-term stability performance. The glassy/vitrified residue is very stable and appears to leach metals only from its exposed surface area. It should be extremely stable over the long run if backfilled on-site or disposed at a landfill. Experimental data indicate that the leachability of the residue is not significantly affected by the pH of the solution and would not, therefore, be affected by anticipated environmental changes.

3.5.4 Residuals treatment/disposal requirements. If treatment can reduce the metals leachability below the EP toxicity levels the glassy/vitrified residue in which the metals are immobilized may be backfilled on-site or disposed in a nonsecure landfill. Off-gases from the process should be minimized by developing the appropriate mixture of additives. Where volatilization is excessive the off-gas would require further treatment. Certain metals will volatilize at low operating temperatures (e.g., arsenic and mercury) and this may result in the problem of treatment or disposal of baghouse dust contaminated with metals.

3.5.5 Flexibility. The process can be used for treating organics contaminated soils for both organics and metals. In fact the process suggests that any rotary kiln soil incineration application which includes metals may be readily modified to reduce the hazardous properties of the residue. It has also been successfully tested for treating metal hydroxide sludges.

3.5.6 Material throughput rate. The roasting process can be conducted in available rotary kiln incineration equipment. Therefore, scale-up should be readily achievable.



3.5.7 Potential disqualifiers.

- (a) Lack of full-scale operational information.
- (b) Control of hazardous gases which may be emitted by the process.
- (c) High energy costs.
- (d) Costs associated with the excavation at the site, backfilling with fresh soil and disposal of the residue.

3.5.8 References.

1. Kox, W.M.A., and E. Van Der Vlist, Conservation and Recycling, Vol. 4, pp 19-38, Pergamon Press, 1981.

3.6 Chloride volatilization.

3.6.1 Description. Heavy metals in the metal chloride form can be removed from the soil as a gas at high temperatures. This is contrary to roasting where the objective is to immobilize the metals in the vitrified residue. Again, most of the work in this area has been performed by the Japanese.

Most metals in soil are in the oxide form. These oxides are not as volatile as chlorides. Therefore, metals must first be converted into volatile chlorides and then vaporized. These volatile compounds are reclaimed from the gas phase and treated or disposed in a suitable manner. In this process, temperature and additives for chemical conversion to chlorides are critical factors. Additives are either chloride salts or other chlorine-containing materials which transform metal oxides to chlorides.

There are no full-scale operational data available for this process. Japanese experimental data are available on the additives and temperatures used in the process. In one experiment, it was found that by adding CaCl_2 to sludge containing Pb, Cd, and Zn, 95 percent removal efficiencies were achieved at $1,100^\circ\text{C}$. Another experiment involved the use of PVC waste as an additive. The drawback with this method is that there is a minimum stoichiometric amount of PVC required in the process. This results in the formation of HCl gas which causes an air-pollution problem. This problem could potentially be solved by adding lime to bind the excess HCl and form CaCl_2 .

3.6.2 Treatment effectiveness. Experimental data shows that the process cannot remove all the metals by volatilization. In one experiment, 95 percent removal efficiencies were demonstrated for wastes containing metals in the low percent range.

Since the process cannot remove all the metals from the soil, the residue will still contain some metals. The experimental data for this particular waste shows that even with a removal efficiency of 95 percent the residual metal concentration is about 0.1 percent. Although leaching data are unavailable, this may be considered hazardous waste for certain metals. Performance data for lower metals concentrations in a soil matrix are unavailable. For low initial concentrations, 95 percent removal could be adequate performance.

3.6.3 Long term stability/performance. Where treatment to adequate total metals concentrations can be achieved, the resulting waste will remain nonhazardous in the long term. If total metals are high and leachable metals are low, subsequent migration may be induced by severe environmental conditions (i.e., high acidity), as might occur with metals in natural soils.

3.6.4 Residuals treatment/disposal requirements. Volatilized metal chlorides must be cooled, condensed, and collected as a dust. Metal concentrations in the residue will be higher but its leaching properties are unknown. Disposal requirements and costs would depend on leachability. Any HCl gas discharged, if PVC wastes are burned, will also have to be treated.

3.6.5 Flexibility. The process is conducted at high temperatures in rotary kiln type equipment and is, therefore, also likely to successfully destroy organic compounds or explosives. It has been shown at the experimental level to be applicable for treatment of sludges but has not been demonstrated for contaminated soils.

3.6.6 Material throughput rate. The process could be implemented using available solids mixing and rotary kiln incineration equipment. Therefore, scale-up should be readily achievable.

3.6.7 Potential disqualifiers.

- (a) The process cannot remove all the metals from the soils. The residual metal levels (based on experimental runs) may be too high from a hazardous waste standpoint.
- (b) Energy costs will be comparable to incineration.
- (c) Residue will require disposal or further treatment.
- (d) Off-gas treatment costs may be high, especially when HCl has to be treated.
- (e) Recovery of the volatilized heavy metal compounds from the gas phase may cause severe problems with respect to cooling, corrosion, and aerosol collection.

- (f) Volatilization, followed by recovery from the gas phase, only causes the heavy-metal problem to crop up elsewhere. The recovered concentrated mixture of potentially soluble chlorides, is not ready for reuse.

3.6.8 Reference.

1. Kox, W.M.A., and E. Van Der Vlist, Conservation and Recycling, Vol. 4, pp 29-38, Pergamon Press, 1981.

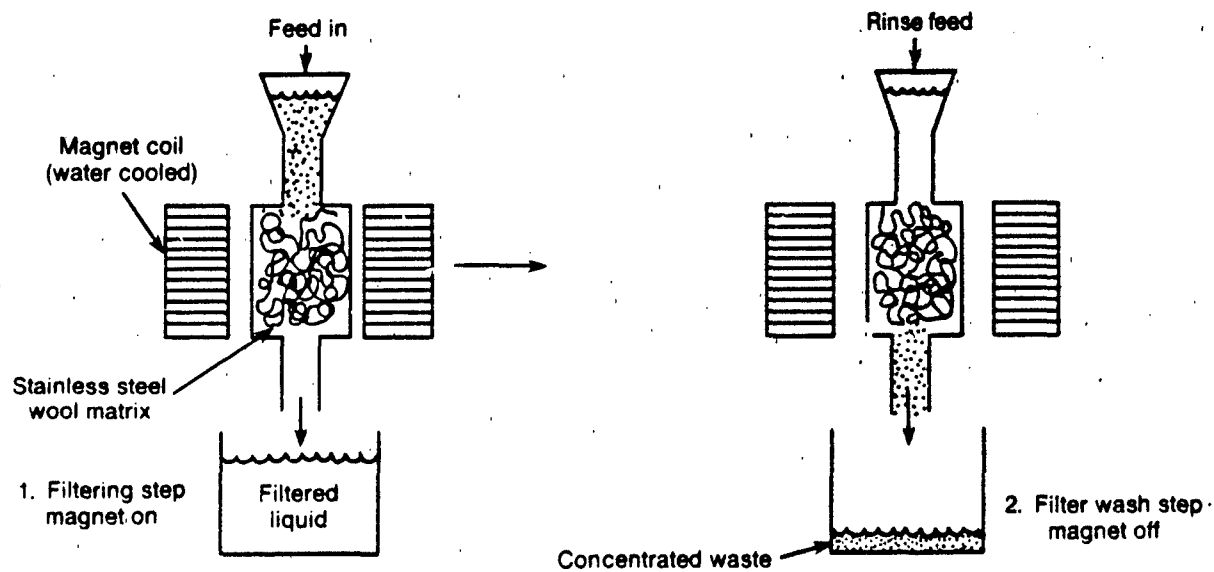
3.7 High gradient magnetic separation.

3.7.1 Description. High Gradient Magnetic Separation (HGMS) has been studied for removal of magnetic or paramagnetic substances from wastewater and certain mineral products including clays and coal. A filamentous ferromagnetic material immersed in a magnetic field provides a high surface area for capture. Stainless steel wool or expanded metal packing have been utilized.

Some nonmagnetic materials may be removed by "seeding" with a ferromagnetic substance such as Fe_2O_3 to create an agglomerate. This co-precipitation process has been utilized successfully for metals removal from wastewater by flocculation/ clarification. Here nonmagnetic metals are bound to a magnetic agglomerate prior to magnetic separation.

The material must be first processed for size reduction and is then conveyed using a water slurry or air. The material passes through the magnetic matrix under a magnetic field of 1,000 to 20,000 gauss. The steel wool is magnetized creating high magnetic field gradients locally around each fiber. This can result in capture of even weakly paramagnetic particles. The magnetic field is periodically removed to release the accumulated metals into a slurry or air concentrate. A process schematic is presented in Figure 8.

HGMS was first commercialized in 1974 for removal of mineral impurities from clay slurries. It may also be applied for recovery of metals from process effluents and low grade ores and removal of iron from river water. It has also been used successfully on a commercial scale for coal desulfurization and demineralization at a rate of 100 tons of dry coal per hour. Capital outlay varies with the strength of the magnetic field. Operating costs are estimated at 1 to 5 dollars per 1,000 gallons for removal of paramagnetic materials from liquids.



Source: Reference 10

FIGURE 8 Schematic representation of HGMS for liquid streams.

While HGMS has been applied to finely-ground dried coal (30 to 100 mesh) using air conveyance, testing is currently being conducted in a joint DOE/DOD/EPA project for separating metals from waste sludges, slurries, or granular mixtures. This study will also determine if diamagnetic materials (those repulsed by a magnet) can be separated by utilizing an open gradient magnetic separator (OGMS). The OGMS process imposes a high gradient magnetic field across a gravity fed flow of material without a magnetized matrix. The paramagnetic or diamagnetic materials are deflected from the vertical and can be captured in separate receiving vessels. This process results in continuous operation and reduced material handling problems. This process has been laboratory tested on a bench scale Franz open gradient magnetic separator. A small super-cooled laboratory pilot unit will be tested as well.

While no test results have been published on OGMS, preliminary results are available for separation of uranium from sand or sandy soils. Thus far, recovery of a uranium rich stream (30 to 50 percent) has been confirmed but the treated stream still retained 0.2 to 0.4 percent uranium.

The applicability of HGMS and OGMS appears to be limited to solid materials which can be separated into contaminated and uncontaminated particles when dried, and reduced in size to 30 to 100 mesh. Its best applications appear to be in metallurgical or mineral processes where impurity removal in the fraction of a percent range is adequate. Further testing will be necessary to determine if lower treatment levels are achievable.

One limitation to the application of HGMS and OGMS to soil or wastes is the magnetic susceptibility of the target compounds. Metals and their various molecular species exhibit wide variations in magnetic susceptibility and with some values very close to major soil components (e.g., silica). As a result, mixed metals and metal species may not be as easily treated as single specie contamination.

3.7.2 Treatment effectiveness. The HGMS process is effective for removal of impurities (ferrous material, pyritic sulfur, ash) from clays and coal where objectives range from fractions of a percent to 40 percent impurities. Removal of metal contaminants in soils to the low ppm range has not been demonstrated experimentally. The process may have limited application for highly contaminated soils with appropriate paramagnetic properties where the metals are separable as particles rather than dispersed. While complete decontamination may not be achieved, HGMS/OGMS may be considered for large applications as a pretreatment/recovery step.

3.7.3 Long term stability/performance. The process would remove metals from the soil. Therefore, if adequate treatment can initially be achieved, the removal of the hazardous properties will be permanent.

3.7.4 Residuals treatment. The HGMS and OGMS processes produce a concentrated liquid or solid waste which will require further treatment and/or disposal as a hazardous waste. In order to achieve a lower concentration in the treated stream, the volume of the concentrate would likely increase.

3.7.5 Flexibility. The process is not capable of treating for organic compounds. It may be able to treat sludges but no benefit is likely for already concentrated sludges. The treatment of incineration residues may be possible only if metals are not dispersed in the slag. The OGMS process is not likely to be useful for mixed property soils like sandy clays because drying and particle size reduction will result in too wide a variation in particle size making separation difficult.

3.7.6 Material throughput rate. HGMS has been demonstrated for large commercial applications (i.e., coal, clay processing). OGMS is a continuous process which does not require backflush cycling (as does HGMS), so scale-up should also be readily achievable.

3.7.7 Potential disqualifiers. The principal concerns for the application HGMS/OGMS are performance and residue management. No other significant fatal flaws have been identified.

3.7.8 References

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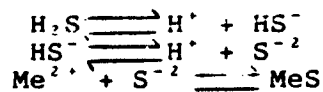
3.8 On-site precipitation.

3.8.1 Description. Precipitation is a process wherein a substance which is in solution is converted to a solid. In this process the solubility of a metal species is altered by reacting it with specific chemicals causing it to "precipitate" from the solution. This process has been used extensively to treat wastewaters containing heavy metals. This approach may be adopted to soils to convert metals to insoluble species and reduce their mobility. The on-site precipitation process would incorporate treatment chemicals with excavated soils using conventional mixing equipment. There is no published literature, however, on the treatment of soils contaminated with metals.^{1,5,8}

Several methods have been developed in the wastewater treatment field for precipitation of heavy metals which might also successfully be applied to soils. The following is a brief description of some of the well-known methods.

3.8.1.1 Sulfide process.

Heavy metals react with sulfide ions to form metal sulfides which are insoluble in water. The generic reactions for divalent heavy metals may be characterized as follows:



Generally, as the pH of the solution increases, the solubility of the metal sulfide decreases. The amount of metal sulfide formed is dependent on the following:

- (a) pH.
- (b) Type of metal.
- (c) Sulfide content.
- (d) Other ions that interfere with the process.
- (e) Salt content of the waste.

In wastewater treatment, sodium sulfide (Na_2S) and sodium hydrosulfide (NaHS) are typically used as the sulfide source in the reduction reaction. However, this may not be possible in the case of soils because sodium may adversely affect soil properties, particularly permeability.

There is some speculation that calcium or iron sulfide may be used. Since they have a low solubility in water, they may be added as a slurry. While wastewater treatment with sulfides has been studied extensively, no experimental work has been done on treating soils. Therefore, there is no information available for soils on the kinetics of the reactions, chemical loading rates, etc.

Most metal sulfides are highly insoluble in water with the exception of certain sulfide complexes formed by zinc, mercury, and silver which are soluble in water.

The solubility of metal sulfides is lower across a wider range of pH than all other precipitating chemicals typically utilized for wastewater treatment. A concern, however, for more acidic soils is the potential for slow evolution of H_2S , a toxic gas. In addition, since sulfide solubilities decrease somewhat with increasing pH, high soil pH may be more favorable for sulfide treatment. While no adjustment of alkalinity would be necessary for naturally alkaline soils, acidic soils may require lime addition to maintain a higher pH.

Under aerobic conditions, metal sulfides can be oxidized to form metal sulfates which are soluble in water. This condition might be controlled by incorporation of soil organic material and/or providing a surface barrier to water or air infiltration but remains a concern for long-term stability of treated soil.

3.8.1.2 Sodium borohydride (NaBH_4) process. This process has been used in several chemical industry installations to treat metal bearing wastewaters. NaBH_4 is a strong reducing agent which can reduce many metal compounds to elemental metals. Where waste streams are contaminated with a single metal, the precipitate may be reprocessed or recycled for recovery of the metal. Where waste streams contain many metals, the advantage of this process over other precipitation techniques is the lower volume of sludge produced. However, this must be balanced against the higher costs of NaBH_4 .

The process involves adjusting the pH of the wastewater to 8-11 and then adding NaBH_4 . The reaction time is approximately 30 minutes for complete metal reduction.²

Again, there is no published literature on the applicability of this process to soils contaminated with metals. NaBH_4 may be applied to the soil as a 98 percent powder or as a 12 percent solution mixed with caustic. The slow reaction rate observed for water may indicate a slower rate in soils. The reduction reaction products will remain stable in a reducing environment, but, as with sulfide precipitation, oxidation and remobilization may subsequently occur unless soil conditions are controlled. Depending on the nature of the metals in the soil, this concept may, upon further study, be applicable for the treatment of metal contaminated soils.

One of the potential hazards associated with the use of this chemical is the evolution of hydrogen, a reaction product.

Cost information is available in the literature for the treatment of metals contaminated wastewaters.²

3.8.1.3 Cellulose Xanthate. This process was developed by the U.S. Department of Agriculture as a low cost means of removing metals from wastewater.³ The typical process scheme is as follows:



Highly Cross-linked Starch + NaOH + CS₂

↓ H₂O, MgSO₄

Insoluble Starch Xanthate (Solid)

↓ Heavy Metal Effluent

↓ Separation (Stir-filter)

↓ Insoluble Metal Starch Xanthate + Clean Effluent

The insoluble starch Xanthate (ISX) acts as an ion-exchanger that rapidly removes heavy metal ions from wastewater, replacing them with Ca²⁺ and Mg²⁺ ions. ISX is mixed with wastewater and subsequently separated and can be used as a filter or packing. Tests have shown that the process can operate in the pH range of 3 to 11 with greater effectiveness achieved at pH values >7.0. Other advantages of this process include the fact that the ISX metal sludge settles very fast and dewateres easily. Also, the sludge can be treated further with HNO₃ to recover the metals. Experimental data have shown that the process can be operated in both the batch or continuous modes with significant metals removal being achieved. While the process is effective, ISX is thought to be too expensive relative to chemical precipitants at metal concentrations above 100 mg/L in wastewater.³

There is no published literature on applications of this process to treatment of metals contaminated soil. Its successful application may be limited by difficulty in distributing the insoluble starch throughout the soil and in its potential biodegradation in a biologically active soil.

3.8.1.4 Lime/carbonates/hydroxides processes. Heavy metal hydroxides and carbonates are insoluble in water. This phenomenon has been used extensively to remove heavy metals from wastewaters. The solubility of hydroxides first decreases with increasing pH up to an optimum pH and then starts increasing again. This behavior is unlike that for sulfides where the solubility continuously decreases with increasing pH.

In wastewater treatment, metals are precipitated out as carbonates or hydroxides by adding lime. pH control is very critical in this process. Solubility curves for the metal hydroxides determine the best operating pH. Since the optimum pH varies widely between metals, a mixture of metals may not all be effectively treated by this method.



This process is followed by a sedimentation step where the metal precipitates are removed from the water by settling. Flocculating agents which improve the settling characteristics of the precipitate are also added, prior to settling, in certain cases.^{1,4,8}

This process has not been applied to the treatment of soils contaminated with metals. A study has been conducted applying lime as a barrier to migration of metals from municipal solid waste leachate to surrounding soils. It was found that metals "breakthrough" a soil column was significantly prolonged when a layer of crushed limestone was utilized, particularly for trivalent chromium. Breakthrough did eventually occur, due to the coating of the crushed limestone, with only partial limestone consumption. The results indicate that soil treatment to reduce mobility may be feasible. Since the solubility of hydroxides is sensitive to pH, applying this process to nonalkaline soils or in regions where the rainfall is acidic, could result in long-term instability and potential remobilization.

3.8.1.5 Application to on-site soil treatment. While these are established processes for wastewater treatment, reduction/precipitation/immobilization of metals in soils has not been investigated. An on-site soil treatment process would first excavate contaminated soil for input to process equipment. It could utilize either a slurry and mixing process or dry mixing process to distribute the treatment chemicals. A schematic diagram of the process is shown in Figure 9.

The water slurry process could very effectively distribute both soluble treatment chemicals (e.g., sodium hydrosulfide) and insoluble chemicals (e.g., lime) throughout the soil. The water and mixing may provide more rapid reaction of soluble metal species to form precipitates. The soil would require dewatering prior to backfill or landfill disposal.

A dry mixing process using large scale solids mixing equipment (e.g., pug mill, screw mixer, etc.) would intimately mix insoluble treatment chemicals with the soil. Reaction may occur at a lower rate since metals dissolved in the soil pore moisture or adsorbed onto soil surfaces may not be in contact with the treatment chemical. The migration of metals to the chemical via percolation or the low level dissolution of the chemical into the soil moisture could prevent migration of unreacted metals from the bulk soil mass.

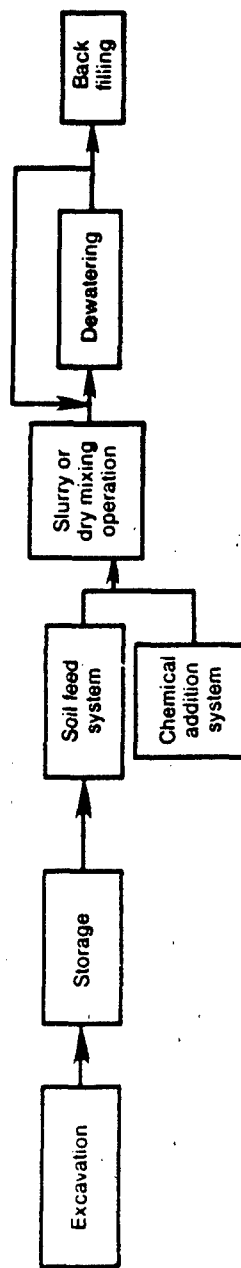
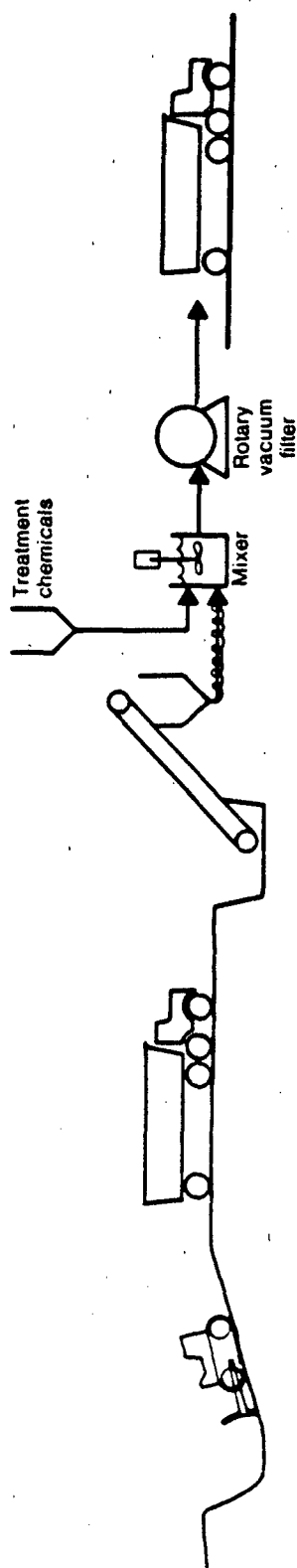


FIGURE 9 On-site precipitation; block flow diagram.



3.8.2 Treatment effectiveness. The process concept, treatment chemicals, dosage, and pH would require further study to determine if performance is acceptable for soil contaminant remediation. The ability of treated soil to meet EP toxicity levels depends on the chemical treatment used. Based on a wider pH range of low solubility, sulfide precipitation may perform best under exposure to mild acids. Other treatment chemicals may require excess addition of alkaline material to maintain high pH through the EP toxicity extraction. Ultimately, preserving performance long-term after backfilling on-site or landfilling may require runoff controls and/or infiltration barriers to prevent exposure to destabilizing acidic or oxidizing agents.

Another option would be to use these processes in conjunction with extractive procedures. In this manner, metals could be first extracted into an aqueous phase and then precipitated out using the above processes. This is considered as part of the extraction technologies.

3.8.3 Long term stability/performance. Since there is no experimental data on the applicability of these processes to soils, comments on treatment stability and performance are based on engineering judgment. One of the problems already identified is the dependence of these processes on pH which would mean that some arrangement for maintaining the pH level by liming etc. would be required to prevent chemical conversion and resolubilization. Soil properties like pH, form of the metals, and oxidation-reduction potential will play a critical part in determining the long-term performance of the process. With metal sulfides, there is a possibility of conversion to water soluble sulfates. Long-term performance is clearly a key concern in successful use of this technology.

3.8.4 Residuals treatment/disposal requirements. One of the biggest disadvantages of the above processes is that the metal precipitates and soil remain together and must be backfilled or disposed. Disposal requirements for the treated soil would depend on extract metal concentrations and anticipated long-term stability. Liquid effluents from the processes could be recycled, discharged, or may have to be treated prior to disposal depending on metals concentrations.

3.8.5 Flexibility. The process is clearly able to treat aqueous wastes containing metals. The process is designed to primarily address metals and is unlikely to effectively treat for organic compounds. While there are no experimental data to prove that these processes can be used to treat soils, if successful, they may also be applied to residues from organic soil treatment processes, including incinerator ash. Since sludges of interest already contain metal precipitates, further treatment may not be effective in altering sludge characteristics.

3.8.6 Material throughput rate. The process may be scaled-up using solids handling and mixing equipment. Scale-up should be readily achievable.

3.8.7 Potential disqualifiers. The most significant potential disqualifier of these processes is performance. Their application to soils treatment is purely conceptual at this stage. Extensive research and development work is necessary to evaluate the feasibility of applying these processes to soils. Depending on the soil chemistry and the nature/form of the metal contaminants, the kinetics of the processes would be different from those used for wastewater treatment. Chemical and handling costs could be considerably higher than those for wastewater treatment. Application of these processes would also involve excavation of the contaminated soil and backfilling of the treated soil. Another disqualification may be the instability of the precipitate vis-a-vis pH of the soil and oxidation of reduction products. Under some environmental conditions (e.g., at lower pH values, oxidative environment) the precipitates may go back into solution. The use of sodium borohydride and sulfides may also present some safety risks due to the potential generation hydrogen and hydrogen sulfide, respectively.

3.8.8 References.

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3.9 In situ precipitation.

3.9.1 Description. The basic theory for this process is the same as that previously described under on-site precipitation. In this process, chemicals are directly applied to the soil to precipitate the metals. The mobility of metals in the soil is decreased, thereby mitigating their harmful effects on the environment. This discussion is limited to the application of precipitation in situ.

The four methods of precipitation or reduction/precipitation are the same as those for on-site precipitation, namely:

- (a) Sulfide process.
- (b) Sodium borohydride process.
- (c) Cellulose xanthate process.
- (d) Lime/carbonates/hydroxides process.

Briefly, the theory behind all these processes is the conversion of soluble metals to insoluble precipitates and thus altering the chemical equilibrium relationship between the solute and the solution.

The application of the above processes to soils contaminated with metals has not been studied in great detail. Most of the experience with these processes has been in the area of wastewater treatment. Generally, metals are present in soil solutions or are attached to electrically charged sites in the solid phase. Therefore, from a concept standpoint, processes for treatment of metal contaminated aqueous wastes should be applicable to soils with metals in the solution phase. Conversion of metal compounds weakly bound to the soil may also be possible, given favorable reaction kinetics. An excess of treatment chemicals may be necessary to assure complete reaction due to competing soil reactions.

Given the variation in soil types, structures etc. and the extent of the contamination, the applicability of these processes would be site-specific. Table 5 contains some site and soil characteristics which are important with respect to in-situ treatment. Heavy metals interact with soils and usually accumulate in natural systems near the surface. Downward transport occurs only when the soils buffer capacity (dependent on soil chemistry) is exceeded. Figure 10 shows the various phenomena that influence soil metal concentrations.

These in situ treatment chemicals could be applied as chemical solutions (e.g., sodium sulfide) and allowed to percolate through the soil to the required depth. Other chemicals (e.g., lime, sodium borohydride) must be applied as a slurry or solid and incorporated into the soil by tilling.

TABLE 5. SITE AND SOIL CHARACTERISTICS IDENTIFIED AS
IMPORTANT IN IN SITU TREATMENT

Characteristics
Site location/topography
Slope of site-degree and aspect
Soil, type, and extent
Soil profile properties:
Depth
Boundary characteristics
Texture*
Amount and type of coarse fragments
Structure*
Color
Degree of mottling
Presence of carbonates
Bulk density*
Cation exchange capacity*
Clay content
Type of clay
pH*
Eh*
Surface area*
Organic matter content*
Nutrient status*
Microbial activity*
Hydraulic properties and conditions
Depth to impermeable layer or bedrock
Depth to groundwater* (including seasonal variations)
Infiltration rates*
Permeability* (under saturated and a range of unsaturated conditions)
Water holding capacity*
Soil water characteristic curve
Field capacity/permanent wilting point
Flooding frequency
Run-off potential*
Aeration status*

TABLE 5. (CONTINUED)

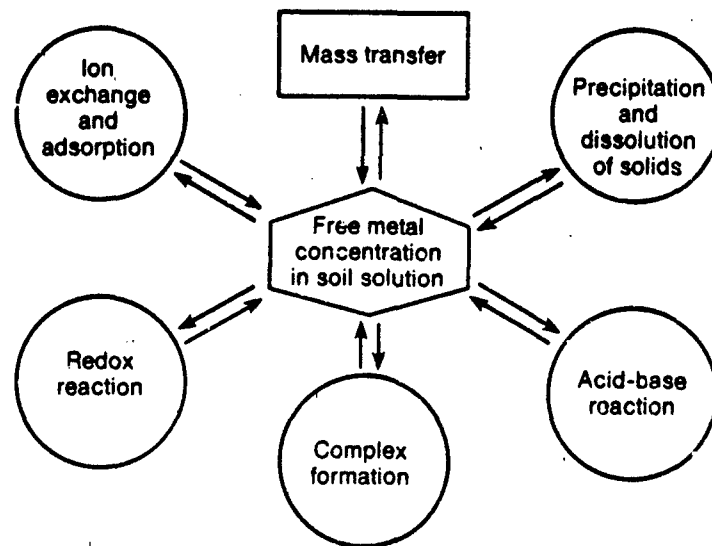
Characteristics
Climatological factors
Temperature*
Wind velocity and direction

*Factors that may be managed to enhance soil treatment.

Source: Sims and Wagner, 1983.

(Manuscripts originally printed in the Proceedings of the National Conference on Management of Uncontrolled Hazardous Waste Sites, 1983. Available from Hazardous Materials Control Research Institute, 9300 Columbia Boulevard, Silver Spring, Maryland 20910.)

Cited in Reference 1.



Source: Mattigod, S.W., Sposito, G. and Page, A.L. 1981. Factors affecting the solubilities of trace metals in soils. In chemistry in the soil environment. ASA special public 40., as cited in Reference 3. [Copyrighted information].

FIGURE 10. Phenomena which influence soil metal concentrations.

Liquid applications would require careful site controls to prevent unwanted surface run-off of chemicals and migration of excess chemicals to the groundwater. Surface controls would include diking and grading. Chemical doses in excess of stoichiometric requirements may be necessary due to competing soil reactions. Doses can be determined by laboratory and pilot testing. Chemical dilution may be necessary to ensure adequate percolation to the desired treatment depth. These measures may result in excess reactants migrating into the groundwater. Although soluble sulfides, carbonates, and hydroxides are not highly toxic in trace quantities, groundwater recovery and treatment or reapplication may be necessary, depending on site hydrogeology and groundwater use.

Following liquid application, additional measures to control the soil environment may be necessary to improve the long-term performance of remedial action. Limestone applied in large doses and tilled into the soil could supply a large buffer capacity to protect against soil acidification in the longterm. Measures to prevent oxidation of reduction/precipitation products may include capping or application of natural organic matter.

The application of slurry or solid chemicals by spreading and tilling would require no special runoff and runoff control measures such as grading and diking since the chemicals have been incorporated into the soil. In fact, limited irrigation may be desirable to consolidate the soil and encourage downward movement and contact of the reactants with the metals. This type of application process may be limited in its effectiveness for contaminated soils well below the ground surface.

A more intensive application procedure for solid or slurry reactants might include mixing at depth using heavy excavating and earth moving equipment. These methods would result in performance and costs between that of on-site precipitation (excavation and mixing process equipment) and surface application.

Following successful reduction/precipitation, post-treatment measures for surface application methods, as described above for liquid application methods, may be beneficial in maintaining performance over the long-term.

3.9.2 Treatment effectiveness. As in the case of in-situ precipitation, the effectiveness of these processes in treating metals contaminated soils has not been established. However, based on the soil chemistry and the information developed for wastewater treatment, these processes could be effectively used to immobilize metals in soil by forming insoluble precipitates. Since applicability of these processes is site-specific, lab tests on the particular soil must be done to determine the best treatment chemicals, dosage, soil pH, mixing requirements, moisture effects, reaction time, and performance. Treated soil should be further studied to determine the effects of environmental stresses (pH, oxidation) on leachability. In addition, pilot studies would be conducted before applying the full-scale process to field situations.

3.9.3 Long term stability/performance. Since the applicability of these processes to soils contaminated with metals has not been demonstrated, estimates on long-term precipitate stability and performance are based on engineering judgment. The long-term effects of changing soil pH and oxidation of reduction/precipitation processes are known to be significant potential destabilizing conditions. Response to these conditions should be studied both in the lab and subsequently on demonstration sites. With additional treatment or site controls which can be utilized to maintain soil pH and a reducing environment, discussed previously, precipitation could be an effective means of immobilizing metals in soil. Of course, long-term reliability will be lower than for technologies which remove metals or convert them to an inert form. This suggests that in-situ precipitation may best be applied to sites with low level contamination or with low risk of migration and exposure. Alternatively, it could be combined with established approaches for low risk sites, such as capping, to provide secondary protection against migration.

3.9.4 Residuals treatment/disposal requirements. Application of any of the above processes to soils contaminated with metals will result in a mixture of soil and immobile metal precipitates. Therefore, there would presumably no residual soil "disposal" requirements. Depending on how the chemicals are applied to the site (e.g., solution slurry or solid form) it is possible that a liquid effluent may be generated (runoff, or groundwater recovery) and require recycling or treatment. If sodium sulfide or sodium hydrosulfide is used to precipitate metals, there is possibility of H_2S emanating from the site, requiring some air pollution control measures. These potential requirements would be determined in the testing and development phase, but are not considered significant obstacles to implementation.

3.9.5 Flexibility. The ability of these processes to treat metal contaminated aqueous wastes has been well-established. Sites with combinations of organic and metal waste contamination may be difficult to treat because of the potential for the formation of water soluble organo-metallic complexes. In addition, these processes are not effective for the treatment of soils contaminated with organics.

Concentrated sludges are typically composed of insoluble precipitates and would only derive potential benefit from agents which maintain the optimum pH to prevent leaching. Since incineration residues are available on the treatment site, in-situ methods and low temperature thermal treatment may not be advantageous.

3.9.6 Material throughput rate. In-situ precipitation can utilize typical farm fertilizer application or spray application techniques to rapidly treat contaminated soils. Established runoff/runoff or groundwater control techniques are also available and readily implementable. Scale-up should be achievable and rates of treatment should far exceed that for on-site precipitation techniques.

3.9.7 Potential disqualifiers. The biggest disqualification is that the applicability of these processes to contaminated soils has not been demonstrated. The costs associated with this technology would probably be lower than that for on-site precipitation because there is no excavation or backfilling involved. The cost is presently unknown but is likely to be lower than landfilling or on-site treatment. Another significant uncertainty is the stability of the precipitates with regard to pH or oxidation-reduction potential.

Other issues include the need for long-term monitoring, the risk of migration of the treatment chemicals and safety hazards associated with sulfide treatment chemicals (H_2S release under acidic conditions) and sodium borohydride (H_2 release from reaction).

3.9.8 References.

1. U.S. EPA Handbook, "Remedial Action at Waste Disposal Sites, EPA/625/6-85/006, October 1985.
2. U.S. EPA, "Review of In-Place Treatment Techniques for Contaminated Surface Soils, Technical Evaluation by Utah Water Research Laboratory, Vol. 1, EPA-540/2-84-003a, September 1984.



3. U.S. EPA, "Review of In-Place Treatment Techniques for Contaminated Surface Soils, Background Information for In Situ Treatment by Utah State University and JRB Associates, Vol. 2, EPA-540/2-84-003b, November 1984.

See On-Site Precipitation for Related References.

3.10 In situ precipitation by vapor phase application.

3.10.1 Description. This technology is a product of recent invention which is suggested by the vapor phase addition of sulfur dioxide for chromium reduction and the addition of sulfides (as iron sulfide or other sulfide salts) for the removal of most heavy metals as metal sulfides.

Gas phase introduction of SO_2 and/or H_2S has some advantages over liquid chemical addition. The gas can be more rapidly distributed due to low viscosity and may more readily overcome hydraulic barriers to liquid percolation.

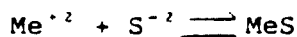
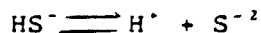
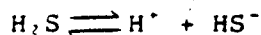
Gas would be circulated via input and withdrawal wells screened in the unsaturated contaminated soil zone. Due to the hazardous properties and high mobility of the gases, precautions would be taken in system design to prevent the release of gases. Withdrawal wells will operate at a vacuum and input wells will operate, as vacuum breakers, near atmospheric pressure. Since the soil system as a whole will be exposed to a vacuum, the soil surface will be sealed to reduce infiltration. Soil sealing may be accomplished by applying a bentonite slurry or asphaltic sealer.

SO_2 or H_2S will be absorbed into the soil moisture or adsorbed onto the soil. Neutralization and reduction or precipitation reactions are then completed in-situ. These chemical reactions are widely utilized in wastewater treatment for metals removal and have been discussed in Subsection 4.8 - On-Site Precipitation.

The reaction for SO_2 reduction of Cr^{+6} has been described as follows:



The anticipated reaction for H_2S precipitation is as follows:



The H_2S precipitation process results in a net addition of acidity to the soil necessitating higher initial soil alkalinity or soil additives to increase alkalinity. While metal sulfides have a low solubility across a wide pH range, metal sulfide solubility increases as pH declines. Low pH will also result in lower H_2S solubility due to the solution equilibrium with Na_2S and CaS .

Gas can be recycled with the addition of H_2S and SO_2 . Some excess gas will accumulate due to net gas leakage into the system. This will require gas treatment prior to discharge to the atmosphere.

In addition to rapid, even distribution of the reactants, this mode of chemical addition can result in less excess chemical addition to the groundwater and soil as compared with liquid phase application. Its principal disadvantage is the safety hazard which could result from the release of gases, particularly the highly toxic H_2S .

3.10.2 Treatment effectiveness. This technology is presently in its early conceptual stage. Performance is likely to be comparable to in situ precipitation discussed in Subsection 4.9. The effectiveness of vapor phase application would depend on reactant solubilities, moisture content and alkalinity in the soil.

3.10.3 Long term stability/performance. Since there is no experimental data on the applicability of these processes to soils, comments on treatment stability and performance are based on engineering judgment. Soil properties like pH, form of the metals, and oxidation-reduction potential will play a critical part in determining the long-term performance of the process. With metal sulfides, the most critical concern is chemical conversion to more soluble species. Under oxidizing conditions, there is a possibility of conversion to water soluble sulfates. As discussed in Subsection 4.8, this might be prevented by incorporating organic matter into the soil and/or surface infiltration controls, but long-term performance is clearly a key concern in successful use of this technology.



3.10.4 Residuals treatment/disposal requirements. Application of this process will result in immobile metal precipitates remaining in the soil. Therefore, there is no residual soil disposal requirement. The excess air extracted from the system necessary to maintain vacuum on the soil may contain residual SO_2 or H_2S . This air stream will require treatment before discharge to the atmosphere. Caustic scrubbing should be effective and may allow for subsequent regeneration of H_2S for reuse. Some absorption of these gases into the groundwater may occur which could result in migration from the site. Although these compounds will tend to oxidize over time to the less hazardous constituents, groundwater management may be necessary where groundwater users may be impacted.

3.10.5 Flexibility. Volatile organic compounds (VOC's) have been successfully treated using in situ volatilization techniques in pilot and full scale operations. This technology would utilize identical gas moving process concepts and so, would be expected to simultaneously apply reactants for metals precipitation and remove VOC's. The excess air stream could be treated for reactants and vented or treated for VOC's. Air venting rates have not yet been established, for in situ precipitation so the compatibility of the two is not certain. Adjustments to reactant concentrations may be made, however, to match the requirements for metals precipitation and VOC removal.

Concentrated sludges are typically composed of insoluble precipitates and would not derive additional benefit from this treatment. Since incineration residues and low temperature thermal treatment residues are available on-site, in situ methods may not be advantageous.

3.10.6 Material throughput rate. The in situ system can be installed over large land areas for simultaneous treatment of the entire unsaturated soil area of concern. The rate of treatment has not been established, but is expected to exceed that for on-site precipitation techniques.

3.10.7 Potential disqualifiers. Although treatment effectiveness (both short and long term) have not been demonstrated, the single largest concern is the unplanned release of toxic gases. While the system is designed to operate largely under vacuum, the reactant, particularly H_2S , present a significant employee safety hazard.

Other potential disqualifiers shared with liquid or slurry based precipitation are the uncertain stability under long term oxidizing conditions, the need for long term monitoring and the risk of migration of treatment chemicals.



3.11.8 References

1. Review of In-Place Treatment Techniques For Contaminated Surface Soils, Volume 1: Technical Evaluation. U.S. EPA, September 1984 - EPA-540/2-84-003a.
2. U.S. EPA Handbook - Remedial Action at Waste Disposal Sites - EPA/625/6-85/006. October 1985.
3. Scott, Murray C. "SULFEXTM - A New Process Technology For Removal of Heavy Metals Waste Streams," Proceedings of the 32nd Industrial Waste Conference, 10-12 May 1977, p. 622, Purdue University, School of Civil Engineering, Indiana 47907.
4. Campbell, H.J., N.C. Scrivner, K. Batzar, R.F. White. "Evaluation of Chromium Removal from a Highly Variable Wastewater Stream," Proceedings of the 32nd Industrial Waste Conference, 10-12 May 1977, p. 102, Purdue University, School of Civil Engineering, West Lafayette, Indiana 47907.

3.11 On-site extraction.

3.11.1 Description. In this process, contaminants are removed from the soil by one or more extraction solutions. The mechanisms for contaminant transfer to the solution phase include solubility, formation of an emulsion or soluble chelation product, and chemical reaction. For metal extraction, reaction by acidification and/or chelation is the predominant mechanism utilized.

This process would involve excavation of the soil and treating it with one or more chemical and wash solutions to remove metals. The wash solution (containing the extracted contaminants) is further treated to remove the contaminants and the clean solution may be recycled to treat the soil or discharged. The number of washes, soil/solution ratios, and other process requirements are determined by site-specific conditions such as soil type, metals present, metal species, etc.

Solvent extraction is used extensively in the chemical process and metallurgical industries. In the latter industry, extensive work has been done on the recovery of metals from ore as well as waste from metallurgical operations. There has been extensive study using an extraction process for treating metal plating waste water followed by selective recovery by precipitation and/or extraction. There is a strong incentive for metallurgical and plating industries to find methods to treat their metal bearing wastes since disposal costs are high and valuable metals are being lost.

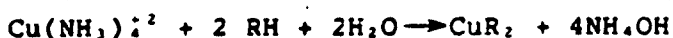
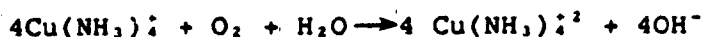
There is recent literature available on the applicability of this process to metal contaminated soils. Investigations range from experimental to field applications. Several solutions/methods have been studied to extract metals from soils. The following are brief descriptions of these methods.

3.11.1.1 Acids/ NH_3 . Both strong and weak acid solutions have been used in the metallurgical industry to extract metals. Acid solutions dissolve basic metal salts like hydroxides, oxides and carbonates. Using strong acid solutions to treat soils may present problems because of potential hazardous residues left in the soil or alterations of soil physical properties. Soils with sufficient alkalinity to buffer acids may be treated with a dilute solution of a strong acid like H_2SO_4 ; otherwise weak acids like acetic acid may be preferred. In one experiment, municipal sludge was treated with sulfuric acid to extract a whole range of heavy metals.² With the exception of Pb, all the heavy metals (Fe, Al, Zn, Mg, Ca, Ni, Ar, Cr and Mn) were extracted to some degree by H_2SO_4 . The extracted solution was then treated with lime to alter the pH and precipitate the metals. A similar acid extraction process has been proposed for treatment of plating sludge at USATHAMA with selective precipitation and extraction for metal recovery. Recovery of metals is less cost effective at lower concentrations especially when there is a mixture of metals.

Bases, like acids, may also be used in certain treatment processes. In an experiment on recovery of metals from electroplating sludge incineration residue, metals were first extracted by using H_2SO_4 and then precipitated by using NaOH. However, the presence of large quantities of iron in the precipitate created problems. The precipitate was then treated with NH_4OH to solubilize all metals except iron.⁴

Material and handling costs would be slightly higher for this process compared to other extraction processes because of the corrosive nature of the acids and bases. Subsequent treatment of the extract will depend upon type and number of the metals present in the soil. Some of the studies directed toward recovery have shown that the process may only be cost effective for large scale plants.⁴

Copper has been recovered from scrap steel by ammonia leaching and solvent extraction. The basic reactions are as follows.⁵



There are similar processes for recovery of heavy metals from solid wastes.⁵

3.11.1.2 EDTA/hydroxyl amine/citrate/water. Ethylenediamine-tetracetic acid (EDTA) is a chelating agent which forms a metal-chelate complex when reacted with metals. These complexes are resistant to decomposition and degradation and can be used as a means of extracting metals from soil. Other chemical agents include citric acid and diethylene-triamine-pentacetic acid (DTPA).

Upon reacting with metals, these agents form complexes, which are soluble in water. The extract is treated to concentrate or recover the metals. The chelating agent should be recycled for cost-effective treatment.

In some soils metals are strongly adsorbed by the magnesium and iron oxides in the soil and extraction with just a chelating agent is not sufficient. In such instances, the metal oxides are first reduced and then mobilized into solution. This is accomplished by adding treatment agents like hydroxylamine and sodium dithionite/citrate along with EDTA.¹

Ellis et al' have demonstrated that a sequential treatment of soil (from an actual Superfund site) with EDTA, hydroxylamine hydrochloride and citrate buffer results in the following metal removal efficiencies: Cd - 98 percent, Pb - 96 percent, Cu - 73 percent, Cr - 52 percent and Ni - 23 percent. Similarly, Connick et al' in an experiment on another Superfund site's soil, have shown that water with EDTA is the most effective reagent for removal of metals. One of their observations was that using water/EDTA/buffer solutions resulted in the formation of precipitates with a resultant decrease in permeability. Finally, work by Castle et al' and related unpublished work shows that EDTA rinse solutions are effective in removing lead only when the soil concentrations are low.

3.11.1.3 Other extraction processes. In some instances, contaminants can be extracted from soil using water alone. Most of the lower molecular weight hydrocarbons can be extracted from the soil with water. Water soluble inorganic salts like carbonates can also be extracted with water'. For metals, a full-scale project has been successfully implemented by the Navy to cleanup soil contaminated with chromic acid at Pearl Harbor, Hawaii.

Other extraction chemicals (for reaction/chelation) remain unexplored which could have potential application for specific metal species and soil characteristics. These may be utilized as a single treatment step or in combination with other chemicals.

There are numerous techniques available for the removal of metals from solution. These should be carefully selected to achieve maximum chemical use/reuse, and to minimize the hazardous properties and volume of residues.

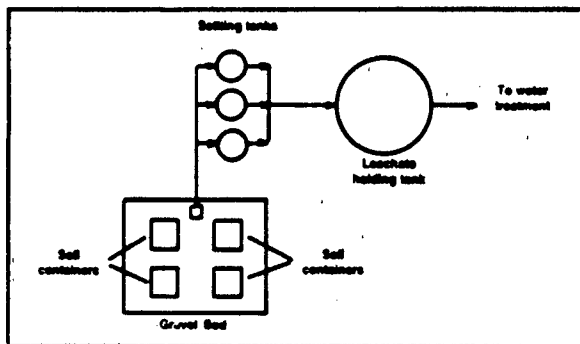
3.11.1.4 On-site extraction process. The use of chelating agents and other additives in removing metals from contaminated soils has been clearly demonstrated at the laboratory level. Many of these tests were done with an intent of evaluating their use in in situ extraction. However, these results are also directly applicable to on-site extraction.

The process can take many potential configurations ranging from simple batch immersion to continuous multistage processing. The Navy's full scale water wash treatment for about 2,200 cubic yards of chromic acid contaminated soil utilized simple batch processing. The washing or "extraction" equipment was essentially a 2-cubic yard dumpster modified with a port at the bottom. The soil was repeatedly washed with water to extract chromium. The extract was subsequently chemically treated to meet discharge standards. The sludge generated by the treatment of the extract was disposed in a hazardous waste landfill while the treated soil was disposed in a conventional landfill because it was rendered nonhazardous. The process for soil and extract treatment is shown in Figure 11.

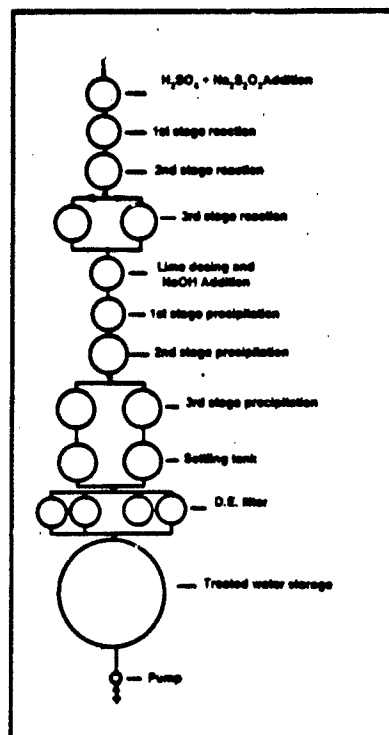
A more complex continuous process was implemented for the cleanup of lead contaminated soils at a Superfund site discussed above. A preliminary flow sheet for this process is shown in Figure 12. The continuous process offers the potential advantage of higher treatment capacity. Disadvantages include difficulties in material handling for soils which may contain rocks and debris, higher solution volume requirements, and more difficult process control for assuring complete treatment.

3.11.2 Treatment effectiveness. Removal efficiencies vary with the type of metal, soil characteristics, choice of reagents etc. Literature seems to indicate that the process is very effective in removing certain metals and ineffective for other metals. Generally Pb seems to be less susceptible to acid leaching and Cr and Ni appear to be less susceptible to EDTA extraction. In addition, the level of cleanup necessary (e.g., EP-Toxicity or human health criteria) would also affect a determination on the effectiveness of a given process. Chromic acid contaminated soil was successfully treated to below EP Toxicity levels by water extraction alone. Laboratory studies indicate that Pb can be removed below EP Toxicity limits by EDTA and other treatment chemicals.

3.11.3 Long-term stability/performance. The result of this process being applied to metals contaminated soil is the production of decontaminated soil. Depending upon the level of cleanup, the treated soil can either be disposed at a nonhazardous landfill or backfilled at the site if satisfactory treatment is initially achieved. There are no long-term problems associated with the treated soil because the contaminants are permanently removed from the soil.



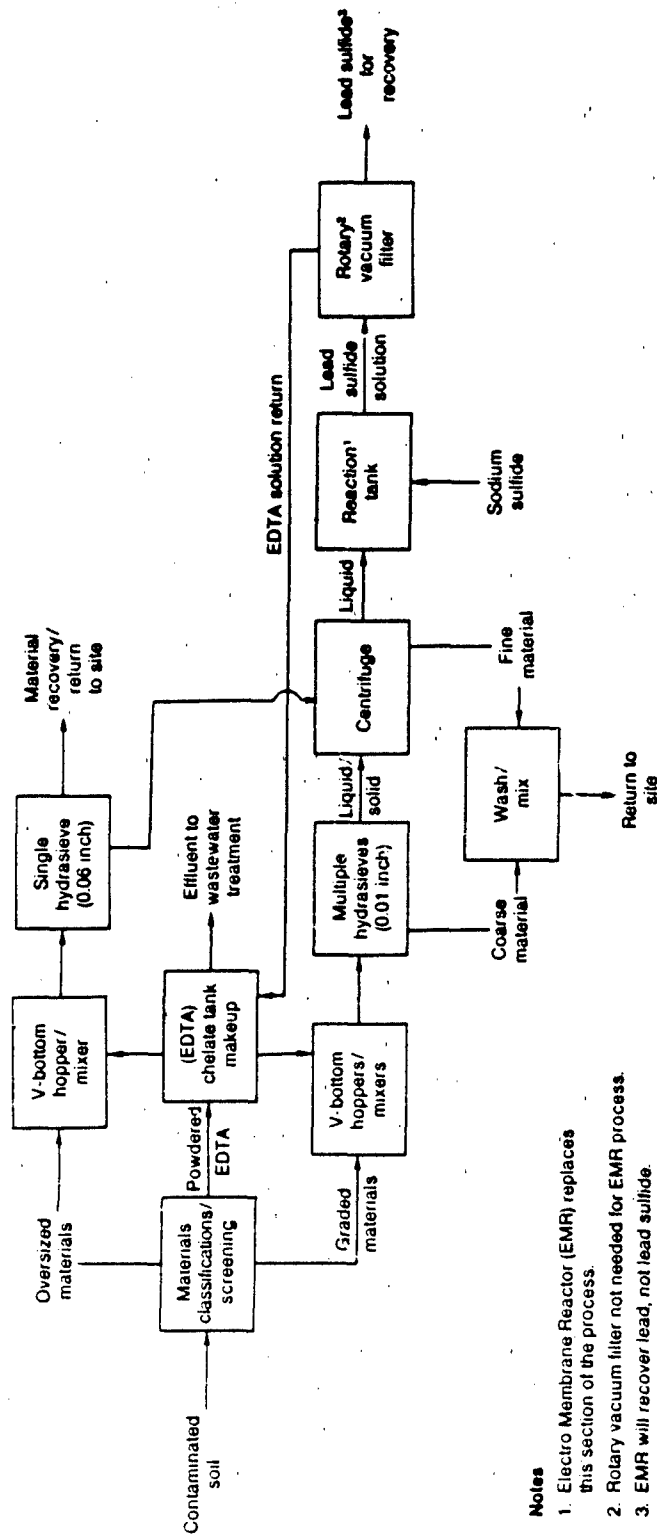
Schematic of soil treatment.



Schematic for leachate treatment.

Source: Reference 6

FIGURE 11. Process flow diagrams for batch soil treatment of chromic acid contaminated soil.



Notes

1. Electro Membrane Reactor (EMR) replaces this section of the process.
2. Rotary vacuum filter not needed for EMR process.
3. EMR will recover lead, not lead sulfide.

Source: Reference 9.

FIGURE 12. Process flow diagram for continuous treatment of lead contaminated soil.

3.11.4 Residuals treatment/disposal requirements. The treated soil may require disposal at a landfill, depending on the residual metal concentrations in the soil. The spent extraction solution containing metals must be treated prior to discharge. The metals may be recovered or concentrated for off-site disposal. Concentration by chemical precipitation may result in hazardous sludges being produced, which in turn must be disposed properly.

3.11.5 Flexibility. The ability of the process to treat metal contaminated aqueous sludges has been demonstrated experimentally. Treatment of incinerator residues has not been studied, but should also be feasible. The process can also be used to extract certain soluble organic materials from the soil. However, combined extraction of organics and metals presents the more complex problem of treating for both simultaneously or separating the organics and the metals in the extract.

3.11.6 Material throughput rate. Treatment at the Navy's soil cleanup site was conducted at a low rate of 40-50 cubic yards/day in a small scale batch operation. Expansion of the dumpsters from 2 to 20 or 30 yards would increase capacity up to 15 times. Additional units in parallel could further increase capacity.

The continuous process could utilize existing ore or construction aggregate processing equipment. While material handling of a mixed soil stream must be carefully designed, scale-up can be readily achieved.

3.11.7 Potential disqualifiers. The ability of the system to handle soils contaminated with metal mixtures is in question because of the problems associated with both extraction and separation of the recovered metals. Material handling costs, while higher in cases where acid or alkaline solutions are used, appear to be comparable to costs associated with disposal in hazardous waste facilities.

3.11.8 References.

1. U.S. EPA - Handbook - Remedial Action At Waste Disposal Sites (October 1985) - EPA/625/6-86/006.
2. U.S. EPA - Removal and Recovery of Metals and Phosphates From Municipal Sewage Sludge (June 1980) - EPA-600/2-80-037.

3. USATHAMA, Aberdeen, Maryland - report AMXTH-TE-TR-85015 - Plating Waste Sludge Metal Recovery - by AMAX Extractive Research and Development, Inc., Golden, Colorado, (May 1985).
4. "The Removal and Recovery of Metals From Sludge and Sludge Incinerator Ash" by B.G. Oliver and J.H. Carey, Environment Canada, Project No. 74-3-15, February 1976.
5. "Handbook of Solvent Extraction," Edited by T.C. Lo, M.H.I. Baird, C. Hanson, John Wiley & Sons, 1983.
6. Yamamoto, V.K., The Navy Civil Engineer, Fall 1984, pp 6-8.
7. Ellis, W.D., T.R. Fogg, A.N. Tafuri, "Treatment of Soils Contaminated with Heavy Metals," 12th Annual Research Symposium: Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste, 21-23 April 1986.
8. Connick, C., F. Blanc, and J. O'Shaughnessy, "Adsorption and Release of Heavy Metals in Contaminated Soil," Environmental Engineering, Proceedings of the 1985 Specialty Conference, 1-5 July 1985 p. 1045.
9. Castle, C., J. Bruck, D. Sappington, and M. Erbaugh, "Research and Development of a Soil Washing System for Use at Superfund Sites," Research and Development (undated) pp. 452-455 plus unpublished internal work by RFW, Inc. on a Wisconsin Superfund site.

3.12 In situ extraction.

3.12.1 Description. The basic theory behind this in situ process is the same as that for on-site extraction. The only difference between the two processes is the manner in which the extraction chemicals are applied to the soil and then recovered. Usually on-site processes are preferred on sites where the contaminated soil has already been excavated as part of a removal action or where removal is mandated by other factor. Unlike on-site processes, this process does not involve excavation of the soil. In situ processes involve application of the chemicals directly to the soil and subsequent recovery of the extracting agent from the elutriate via the groundwater table. While it eliminates the cost of excavation and backfilling, the use of in situ processes results in a risk of contaminating the groundwater at a site, and may result in dilution of the elutriate and less efficient raw material utilization.

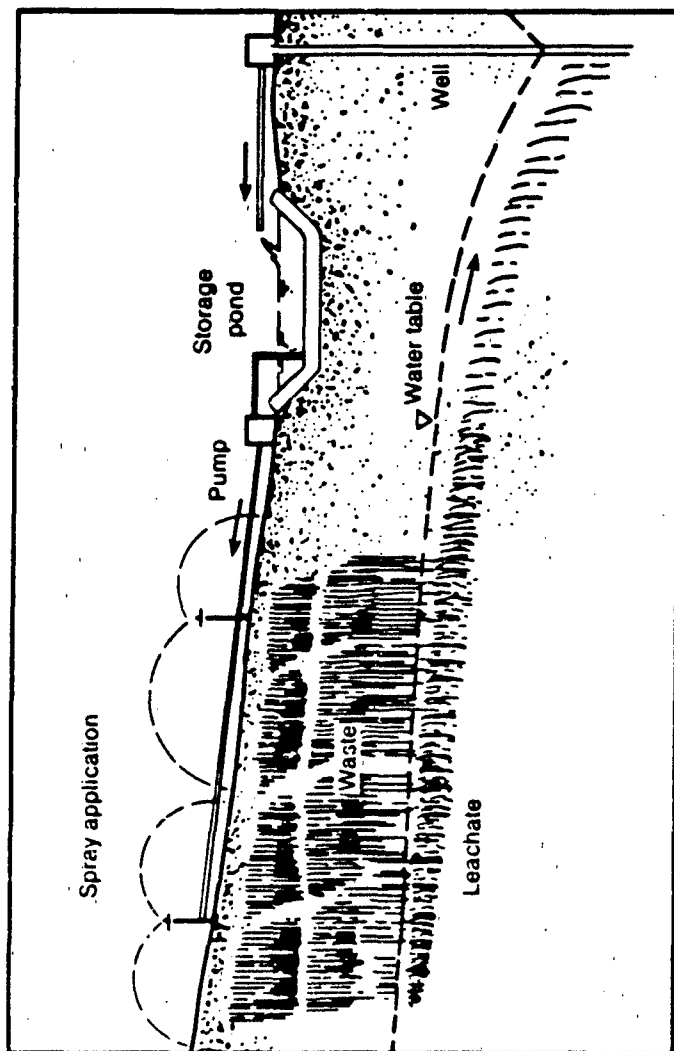
Extract solutions are applied by spray application or flooding the contaminated site. The elutriate is subsequently recovered through subsurface drains or shallow well points. The recovered elutriate is treated to recover the contaminants or concentrate them for disposal. Where expensive complexing agents are utilized the treated elutriating solution should be recycled through the site. If the elutriate is not completely collected by either the subsurface drains or the shallow well point system, then there is a potential risk of contaminating ground or surface waters.¹ Figure 13 shows a schematic diagram for this process.

An obvious advantage of this process over on-site extraction, is that there are no costs associated with excavation and handling of the soil. One disadvantage is the potential for short circuiting of low permeability soils at sites with a heterogeneous soil profile.

Site specific conditions like soil types, chemistry, form of contaminants etc. will dictate operating conditions such as extraction chemical selection, solution concentration, number of flushes and rinses, etc.

Literature contains the results of several experiments on methods for extracting metals from soils and sludges. They included shaker tests to evaluate the ability of the elutriating solution to remove the metals and subsequent soil column tests to determine metal removal from soils under continuous gravity flow. The types of elutriating solutions used in this process are the same as those used in on-site extraction namely acid/NH₃ and EDTA/hydroxyl amine/citrate/water.

Ellis et al² have shown through experiments that sequential treatment of soil (from a Superfund site) with EDTA, hydroxylamine hydrochloride and citrate buffer was effective in removing metals from soil. They have also shown that all these solutions are necessary to achieve the following metal removal efficiencies: Cd - 98 percent, Pb - 96 percent, Cu - 73 percent, Cr - 52 percent and Ni - 23 percent. In an another experiment, Connick et al¹ have shown through column tests that metals can be removed from soils by washing them with water and EDTA. Castle et al⁴ claim that Pb can be recovered from contaminated soils by using an EDTA solution. However, some unpublished internal WESTON work related to this research effort (on a Wisconsin Superfund site) shows that the process is effective only at sites where the lead concentration in the soil is low.



Source: Ehrenfeld, J.R., Bass, J.M. - USEPA -
 Handbook for evaluating remedial action
 technology plans. (1983). EPA-600/2-83-076.
 MERL, Cincinnati, OH. Cited in Reference [1].

FIGURE 13. Schematic diagram of an in-situ extraction process.



While there have been a few applications of the extraction process to on-site extraction of metals, pilot or full-scale in-situ extraction installations for metals are known.

3.12.2 Treatment effectiveness. All the experimental data and limited field applications show that the process can be effective in removing metals. However, removal efficiencies depend on a number of site specific conditions and the correct choice and sequence of solutions.

Ideally the soil should be uniform and have moderate to high permeability. Sites with existing groundwater contamination are preferred since will not result in new contamination and combined soil treatment and groundwater treatment is possible. Given appropriate site conditions, effective in-situ treatment should be achievable.

3.12.3 Long term stability/performance. Laboratory scale performance data indicate that the process is effective, to varying degrees, in removing metals. From a concept standpoint this process has good long-term implications in that the source of contamination is removed from the soil. In-situ treatment performance is typically monitored by discrete soil boring analysis. Therefore, inhomogeneities, including low permeability zones, which are not adequately treated may initially go undetected.

3.12.4 Residuals treatment/disposal requirements. The biggest advantage of this process is that the soil is treated in situ and no disposal of the treated soil is necessary. However, the elutriate has to be treated to remove the metals. Depending upon the economics, the metals may either be recovered or would have to be disposed, possibly in an approved hazardous waste landfill. In some instances, elutriating solutions are used on a once-through basis and would have to be discharged following treatment.

3.12.5 Flexibility. Experimental data show that extraction methods can be used to remove metals from sludges and liquids. The data also show that the process can be used to treat soils contaminated with organics as well. However, treatment of soils contaminated with both may be difficult and would interfere with the ability to recycle expensive metal chelating agents. Sludge or incinerator residue treatment in-situ is not likely to be advantageous.

3.12.16 Material throughput rate. The process is very well suited to treating large soil areas. Treatment is expected to be completed sequentially from the surface down to the depth of solution collection.



3.12.7 Potential disqualifiers. The biggest risk in using this process is the potential for contaminating migration pathways like ground and surface waters. Also, site conditions and present use may preclude or limit the use of this process at some locations. Certain metals and soils may not be amenable to efficient removal.

3.12.8 References.

1. U.S. EPA - Review of In-Place Treatment Techniques for Contaminated Surface Soils," Volume 1: Technical Evaluation. (September 1984) EPA-540/2-84-003a.
2. Ellis, E.D., T.R. Fogg, and A.N. Tafuri, "Treatment of Soils Contaminated With Heavy Metals," 12th Annual Research Symposium: Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste, 21-23 April 1986.
3. Connick, C., F. Blanc, and J. O'Shaughnessy, "Adsorption and Release of Heavy Metals in Contaminated Soil," ASCE Environmental Engineering Division, Proceedings of the 1985 Specialty Conference, 1-5 July 1985, P 1045, Boston Massachusetts. Published by ASCE, New York, New York.
4. Castle, C., J. Bruck, D. Sappington, and M. Erbaugh, "Research and Development of a Soil Washing System for Use at Superfund Sites," Research and Development, undated, pp. 452-455 plus unpublished RFW, Inc. internal correspondence on the Lee's Farm Superfund Site in Wisconsin.
5. U.S. EPA - Case Studies 1-23: Remedial Response at Hazardous Waste Sites (March 1984) EPA-540/2-84-002b.

3.13 Vegetative uptake.

3.13.1 Description. The use of plants which selectively absorb metals from soil and concentrate them in the plant biomass has been suggested as a means of removing metals from contaminated soils. The idea would involve growing specific plants on a metals contaminated site and harvesting the plants at the end of the growing season. The harvested plants must then be disposed in an appropriate manner (e.g., incineration).



The natural phenomenon of metal uptake by plants is dependent on a number of factors such as plant species, soil chemistry and types, and metal species. Generally, metal uptake is higher in acidic soils due to the higher solubility of most metal species at low pH. The soluble metal ions must then move to the roots by movement of soil moisture or diffusion or the root will move by growing through the soil. Cation adsorption is highest at pH 5 to 7 and anion adsorption is best under pH 6.^{1,2} Differences in metal uptake between plants depends on nutrient requirements and typical growth conditions. Many plants concentrate metals only in the roots, indicating that the root surface ion exchange and/or membrane surface characteristics may present a barrier to metal adsorption into the plant tissue. Other plants which typically grow in high mineral content soils, tolerate high metal intake by storage of metals by complexing them with natural ligands.¹ Studies indicate widely varying properties based on the soil matrix and plant species.

Extensive research has been conducted on the uptake of metals from natural soils, urban soils, and sewage and sludge amended soils.^{3,4,5,6} Research on aquatic plant uptake of metals has also been conducted.^{7,8,9}

Much of the work conducted on soils was directed at public health impacts due to metals uptake to food crops. This has shown that metals levels are often increased but not to toxic levels. If metals concentrations are too high, toxicity can result. These studies do not indicate high rates of metal uptake however, with one study citing 1-2 percent uptake of Cd, Cu, Pb, Ni, and Zn in Bermuda grass.⁵

Water hyacinths and alligator weeds have been fairly effective in removal of soluble trace metals (Cd, Ni, Pb, Hg, Co, Zn) from water. Dry weight plant metal concentrations were below 1 mg/g (1,000 ppm) for individual metals. Water concentrations were reduced to detection limits of 1 ppb.^{7,8,9}

Little study in vegetative uptake has been directed toward the objective of maximizing the removal of heavy metals from soil. If plants which perform effectively can be identified, then they can be harvested and disposed. Due to phytotoxic effects on plant growth, applications may be limited to lower metal concentrations. Plant uptake may result in concentration of metals but this is limited in biological systems. This results in a significant residual vegetation volume which will require further management. Disposal in a hazardous waste landfill is an option for this residue. Alternatively, drying and incineration can result in significant volume reduction but metals will remain the ash or off-gas dust and possibly require disposal as a hazardous waste.



3.13.2 Treatment effectiveness. Although much work has been published on vegetative uptake, as described above, few have been directed toward cleanup of metal contaminated soils. The study by Brown, et al¹ indicated that only 1-2 percent of metals in the soil can be removed by Bermuda grass.

Harward et al² conducted a detailed study on the feasibility of using vegetative uptake as a means of cleaning a site contaminated with radionuclides. They calculated that the time required for cleaning up a hypothetical site of 1 acre contaminated to a depth of 6" would be unreasonably long (6.7 x 10⁵ years). Therefore, they concluded that this method was not feasible for radionuclides investigated (Pu, U, Th, Ra).

Any treatment achieved would necessarily be limited to the active plant root zone. Based on the limited information available, it appears that the time involved in cleanup of a site using this "process" is very great. In addition, significant concentration of metals may not be achievable by plant uptake alone. Additional treatment (i.e., incineration) is necessary. Therefore, this method is not likely to be an effective means of removing metals from soils.

3.13.3 Long-term stability/performance. Once removed, of course, the site will remain free of metal. From a long-term perspective this method may be considered ineffective because of the very slow rate of metals removal. During an extended cleanup the metals may migrate off-site or away from the root zone before recovery is achieved.

3.13.4 Residuals treatment/disposal requirements. The harvested vegetative matter containing metals will require disposal. If directly landfilled a large volume must be managed. If dried and incinerated, off-gas dust collection may be necessary and ash and dust residuals containing metals will require disposal.

3.13.5 Flexibility. Removal of organic compounds with aquatic plants has been shown to be effective for low concentrations. Performance by plants selected for their ability to absorb metals remains a subject for future study. Vegetative uptake could be applied to residues where soil properties have been maintained sufficiently to support plant growth. Incineration residue is unlikely to meet these requirement, but other, nondestructive soil treatment residues could be treated.



3.13.6 Material throughput rate. This technology could readily be applied to large land surface areas utilizing normal agricultural techniques. It is, however, limited to treatment of the soil root zone.

3.13.7 Potential disqualifiers. Potential disqualifiers include:

- (a) Very slow removal rates for certain metals renders the process ineffective.
- (b) Extensive long term site management requirements including harvesting of crops.
- (c) Harvested crop/vegetative matter has to be disposed.

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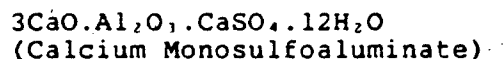
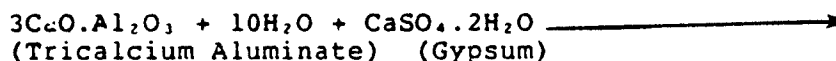
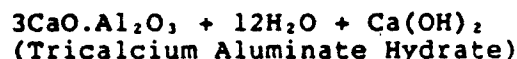
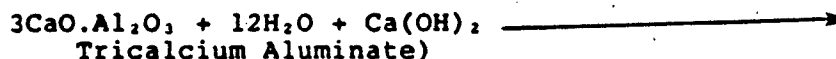
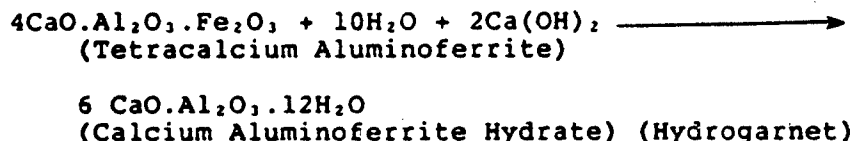
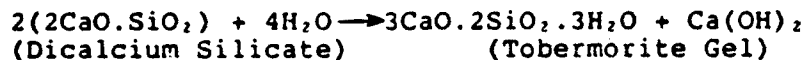
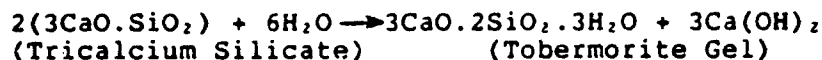
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3.14 Stabilization (admixing).

3.14.1 Description. In this process the waste constituent is immobilized by chemically reacting it with an admixture. The reacted constituent then gets bound in the solidified mass which results in a reduction in the amount of metals that can be leached. An ideal stabilization system would result in a waste constituent being rendered chemically nonreactive and immobilized.¹ There are several commercial stabilization processes which have been used to treat industrial waste and radioactive sludges. The method was first widely accepted in Europe and is now being used extensively in the U.S., particularly for high water content wastes which are subject to land disposal restrictions.

Some of the numerous commercial stabilization systems are proprietary, but there are essentially two primary techniques for stabilization, cement based and lime based techniques.

3.14.1.1 Cement-based techniques. These processes involve the use of Portland cement and other additives such as fly ash to form a concrete type (rock-like) material.¹ Some of the early work done on the treatment of electrochemical plating sludges showed that the forming of concrete was similar to the formation of natural minerals.¹ These researches represented the chemical reactions which occurred in the hardening of concrete, as follows:²

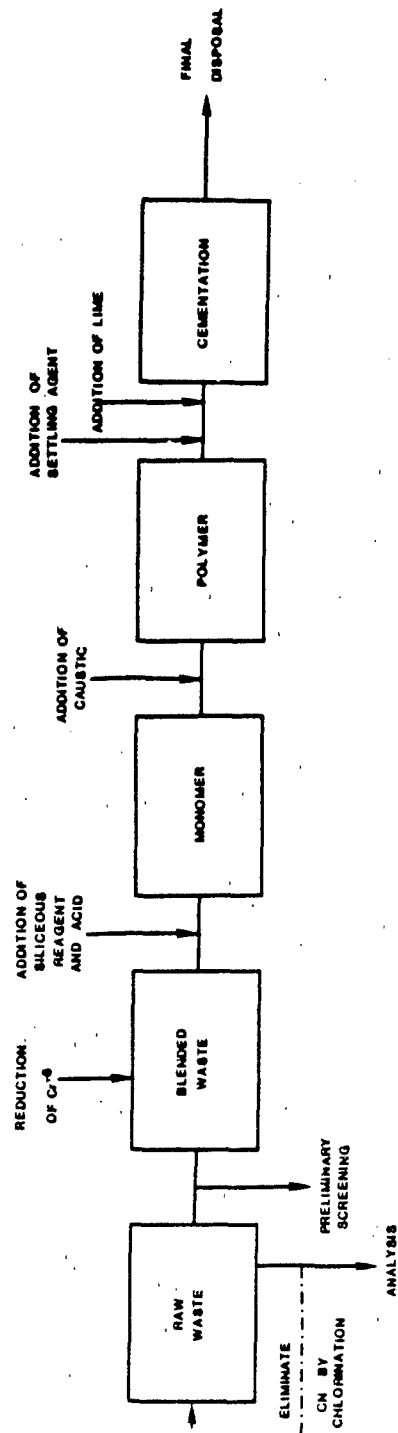


As mentioned previously there are several commercial processes. These processes differ in the use of proprietary additives to enhance the formation of concrete.

Soils from sites contaminated with metals would first be excavated and slurried with water (if necessary). Cement and other additives would then be mixed with the soil slurry. The resultant mixture is then allowed to set to form concrete. Specific process parameters such as the amount of water required, cement formulation requirements, etc must be determined for each soil based upon site-specific conditions. Figure 14 shows a process flow diagram for the commercial Soliroc Process.⁴

The type of cement used depends on type of waste e.g., Type I - normal cement used in construction, Type III - highly early strength, recommended for use where rapid set is required, Type V - special low alumina, sulfate-resistant cement, recommended for high sulfate content (>1,500 mg/kg) waste.¹ This process can be used in a batch or continuous mode. Advantages of this process include:

- (a) The moderate price of additives.
- (b) Availability of processing equipment.
- (c) Proven ability of the process to immobilize metals



Source: Reference 4.

FIGURE 14. Flow diagram for the Soliroc Process.



Some of the disadvantages of using this process are:

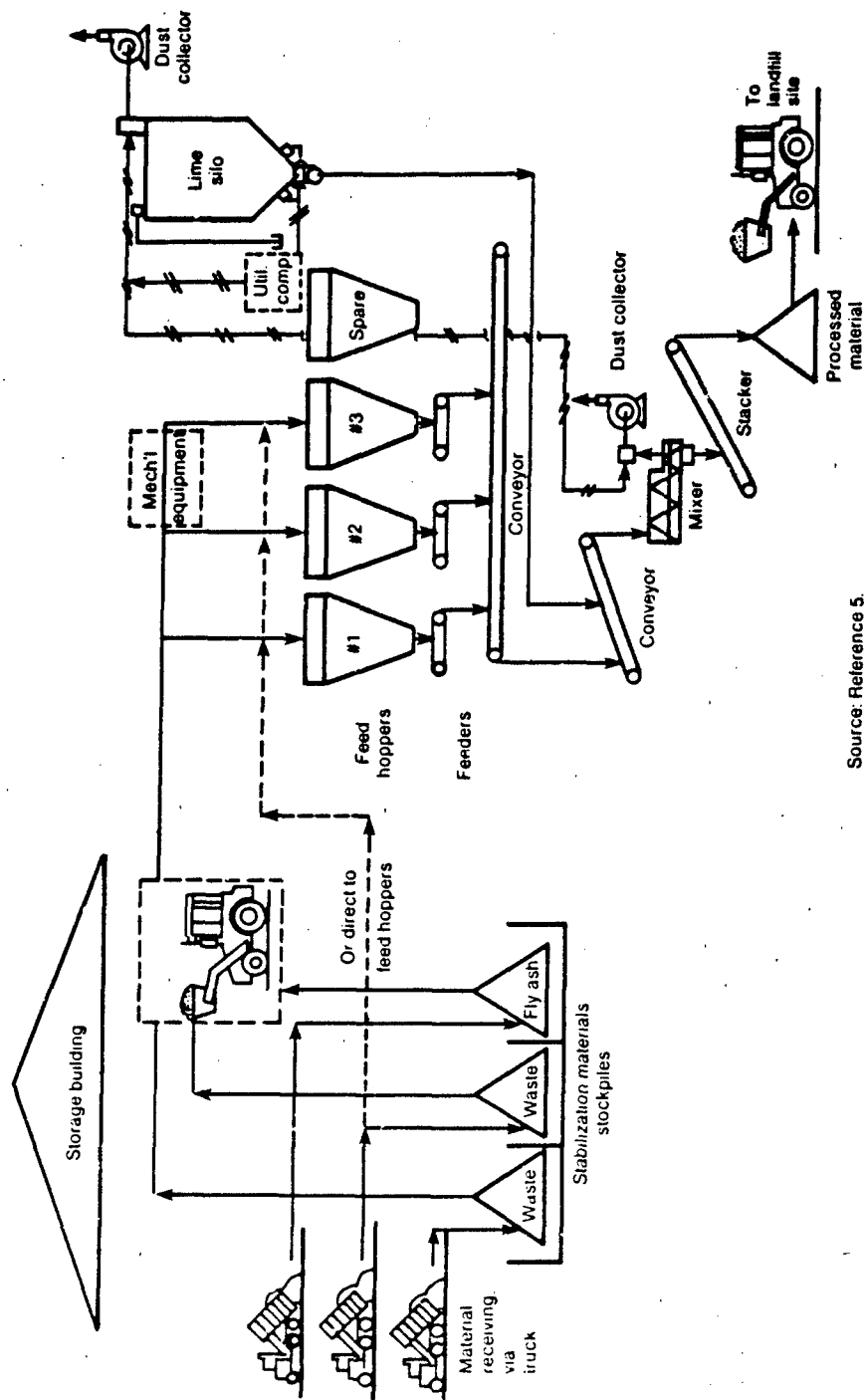
- (a) Metals may be leached from low strength cement-waste mixture by highly acidic solutions.
- (b) Pretreatment may be needed to eliminate certain specific waste constituents.

3.14.1.2 Lime-based techniques. These techniques make use of the reaction of lime with silica and water to form a hard, concrete-like material, often called pozzolanic concrete. Additives like fly-ash, cement-kiln dust and other (possibly proprietary) materials are added to the process in order to increase the strength of the concrete or to retard the migration of the metals in the concrete.²

As in the cement-based techniques there are several commercial processes which use various additives to form pozzolanic materials. Figure 15 shows a process flow diagram for the Envirosafe process used to treat sludges and liquid wastes.³ Adding lime to the waste results in the pH being raised and the metals being rendered insoluble. Adsorption and ion exchange are also enhanced by the pozzolanic reactant and products. Soil with metal contaminants is slurried and treated with the pozzolanic reactants to yield a rock-like material which can be landfilled. The advantages of this process include low costs for additives, well established process chemistry and ease of operation of processing equipment. One of the disadvantages of this process is that the treated material is susceptible to attack by highly acidic solutions.¹

3.14.2 Treatment effectiveness. The ability of this process to effectively immobilize metals in liquid wastes and sludges has been demonstrated at all levels, experimental, pilot-scale and field operational.¹⁻⁴ Based on the available literature, soils contaminated with metals can also be effectively treated using these processes. The choice of the type of process will depend on the site-specific conditions. Tables 6 and 7 show the effectiveness of the Soliroc and Envirosafe processes in immobilizing metals.

3.14.3 Long-term stability/performance. The concrete like material which is formed by the process should be stable over the long-term. Leachate tests have been performed on these materials and they have shown that the extract contained metal concentrations below EPA's EP Toxicity limits.⁵⁻⁷ When the treated waste is tested for EP Toxicity the maximum specified acetic acid mass is added and pH will remain above 7, thereby



Source: Reference 5.

FIGURE 15. Flow diagram for the EnviroSafe Process.

maintaining treated waste stability. Under severe, highly acidic conditions, the material can destabilize, but these conditions are not expected in the environment. Physical tests have shown that the concrete-like product has a low permeability and high strength. This should further improve performance from that indicated by EP Toxicity procedures.

3.14.4 Residuals treatment/disposal requirements. The concrete-like product with the immobilized metals must be disposed in an appropriate manner. Depending upon the nature of the soils, metals concentration, and stabilization performance, the stabilized product may have to be classified/delisted prior to ultimate disposal as a non-hazardous waste. The usual mode of disposal is landfilling but, given the high strength characteristics of the product, it has been used as backing for roads and runways for non-hazardous materials.

3.14.5 Flexibility. The ability of the process to handle liquid wastes and sludges has been well established. Residues from organic contaminant treatment can also be readily treated.

Organic wastes present a problem in that they interfere with the concrete setting. Therefore, wastes with high organic content and metals may not be amenable to treatment.

3.14.6 Material throughput rate. The process has been in full scale commercial use. Conventional batch or continuous feed and mixing equipment may be utilized. Large capacity can be achieved by increasing equipment sizing or utilizing parallel process lines. There is no problem with scale-up.

3.14.7 Potential Disqualifiers. Potential disqualifiers include:

- (a) Organic wastes interfere with the process.
- (b) Low-cement product and pozzolanic cement product are susceptible to attack by highly acid solutions.

TABLE 6. COMPARISON OF RAW WASTE METAL CONCENTRATIONS WITH
EP TOXICITY CONCENTRATIONS AFTER STABILIZATION BY THE
SOLIROC PROCESS

ANALYSES RESULTS OF RAW WASTE SAMPLES
(mg/L EXCEPT AS NOTED)

Sam- ple No.	pH ^a	CN	Cd	Cr	Cu	Ni	Pb	Zn
1	1.0	1.27	15,400	57,000	450	305	4.00	180
2	13.0	2,430	910	535	1,850	5,800	0.74	5,400
5	10.1	968	782	3,890	25,500	1,330	2,000	28,700
6 ^b	13.2	33.7	35.2	440	13,800	5,660	6,580	5,030
7	<1.0	c	53.0	470	39.0	46.0	c	5,000

^apH units.

^bMetal concentrations are given in units of ug/g (wet weight of sludge), as received.

^cAnalysis not performed.

TABLE 6. (CONTINUED)
ANALYSES OF EP EXTRACTS (mg/L)

Run No.	CN	Cd	Cr	Cu	Ni	Pb	Zn
1	^a	5.60	0.10	0.28	1.30	0.013	34.8
2	^a	2.30	0.27	0.64	0.95	0.016	5.00
4	^a	0.10	0.13	0.06	0.15	0.006	0.41
5	^a	2.70	0.18	0.36	1.15	0.017	25.0
6	^a	<0.01	0.50	0.05	<0.10	0.008	0.50
Maximum allowable concentration		1.0 ^d	5.0 ^d	100 ^e	^f	5.0 ^d	500 ^e

^aCharacteristic of EP toxicity from RCRA (100 times NIPDWS).

^d100 times the secondary maximum contaminant level.

^fNickel is not regulated by the primary or secondary drinking water standards.

^sCyanide removed by pretreatment with H₂SO₄ pickling liquor.

Source: Reference 4

TABLE 7. COMPARISON OF CHEMICAL CHARACTERISTICS
AND PHYSICAL CHARACTERISTICS OF WASTES
SUCCESSFULLY STABILIZED BY ENVIROSAFE PROCESS
GENERATOR-TYPICAL STEEL CORPORATION,
WASTE-AIR POLLUTION CONTROL RESIDUE, ELECTRIC FURNACE DUST

Parameter	Chemical characteristics		
	Raw waste DWB ^a (mg/kg)	Stabilized waste ASTM method A Leachate analysis (ppm)	
		RCRA standards (ppm)	
Total solids (%)	99.8		
TOC	840	30	
pH	11.8	11.6	
Oil/grease	479	12	
Ag	235	0.05	5.0
As	34	0.01	5.0
Ba	10	0.75	100
Cd	1,680	0.01	1.0
Cr	1,155	0.15	5.0
Hg	2.8	0.2	0.2
Pb	49,600	5	5.0
Se	2.0	0.07	1.0

Physical characteristics

Unconfined compressive strength: cured 7 days @ 100°F (psi)	>100
Unconfined compressive strength: cured 28 days @ 73°F (psi)	>150
Permeability (cm/sec)	<1 x 10 ⁻⁵

^aDry weight basis.

Source: Reference 5.



3.14.8 References.

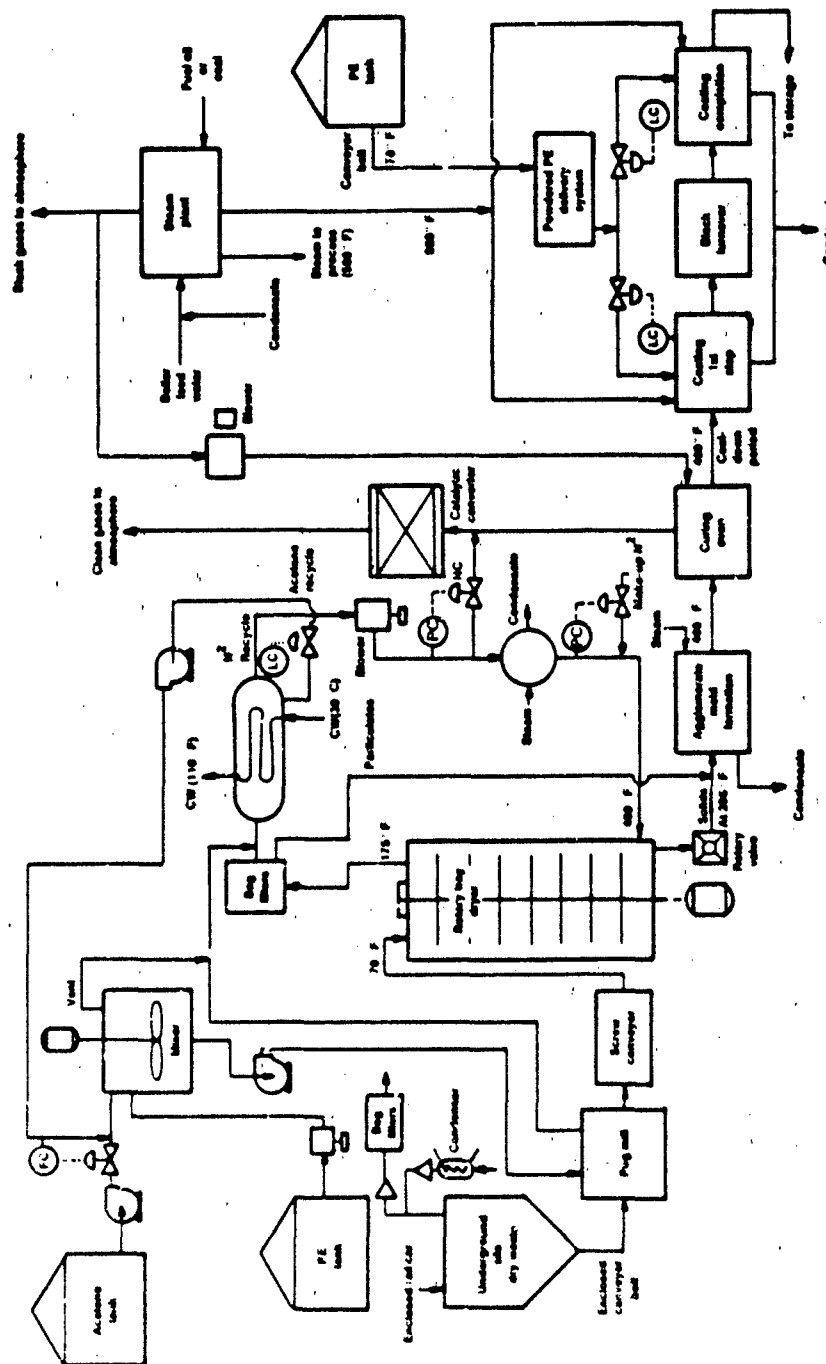
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3.15 Macroencapsulation.

3.15.1 Description. This process involves encapsulation of a block of hazardous waste with a polymer like high density polyethylene to render it environmentally acceptable. There have been a few experiments and pilot scale studies to evaluate the capability of different types polymers to provide an acceptable and stable covering. The most detailed study to date is the one performed by TRW, Inc. for U.S. EPA in 1977. This detailed study first looked at the suitability of certain polymeric materials as liners. Laboratory tests were performed on 3" waste cubes (bound internally with a polybutadiene binder) encapsulated with a 1/4" thick polyethylene jacket. This is actually a more secure combined micro- and macro-encapsulation process. These tests showed that the encapsulation resulted in the retention of the contaminants in the waste even when subjected to severe leaching conditions. Mechanical tests also showed that the encapsulated wastes were capable of withstanding compressive stresses. The product of this treatment process could be disposed in a nonhazardous landfill.

Subsequent TRW study included the development of a process design and cost estimating. Figure 16 shows the process flow diagram for a full-scale waste encapsulation process. This process would yield a 2 foot cube of waste, weighing from 600-1,000 pounds, encapsulated by a 1/4" polyethylene jacket. Cost estimates indicated that treatment cost would be \$91/ton of waste (for a 20,000 ton/year throughput, 1977 cost). Fifty percent of this cost was attributed to the cost of the covering (HDPE) and binding (polybutadiene) resins. This does not include costs for excavation, backfilling and encapsulated waste disposal in a nonhazardous landfill. The researchers have specifically recommended this process for treating metal contaminated wastes.



Source Reference [1]

FIGURE 16. TRW process flow diagram.

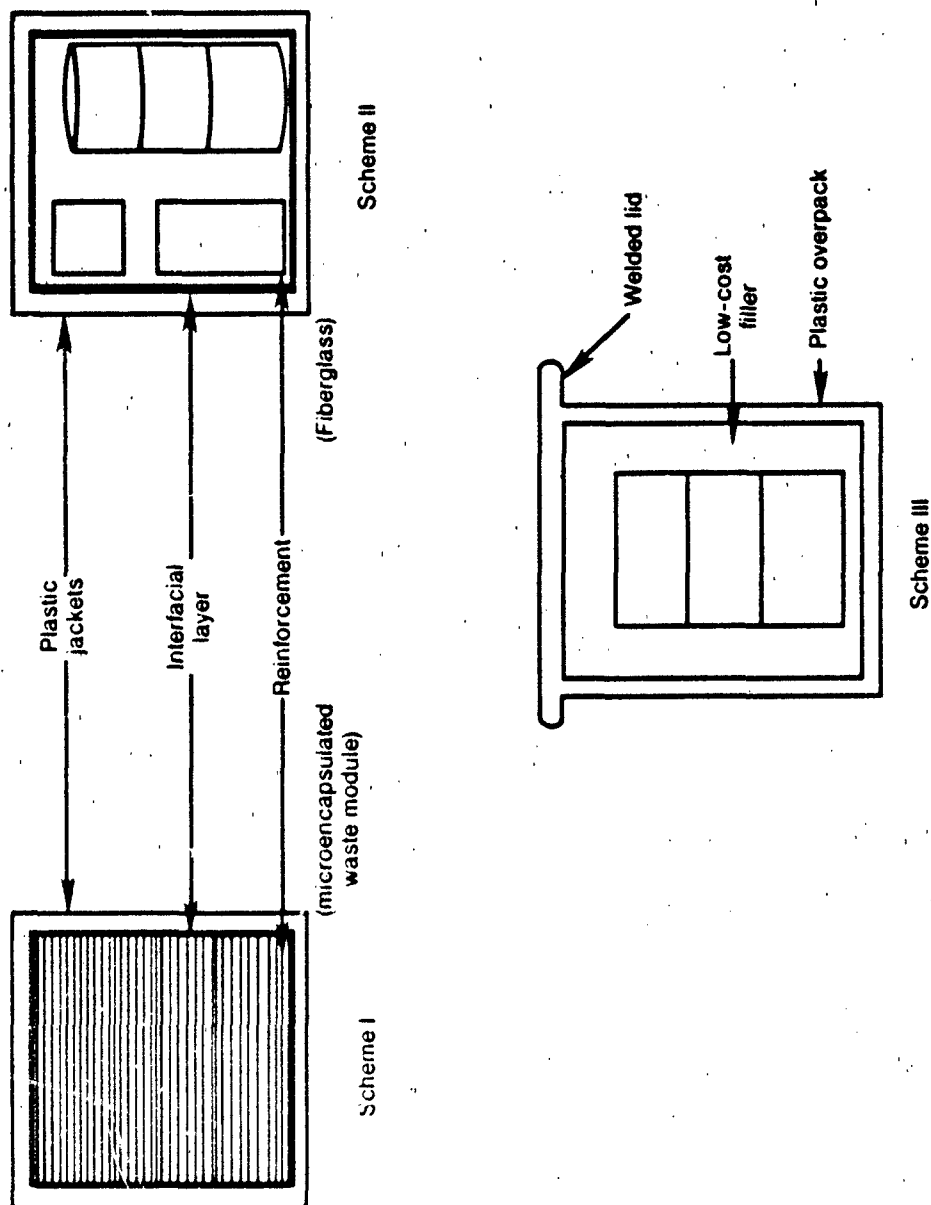


Lubowitz and Wiles² reviewed three methods for encapsulating hazardous waste. The first method is the TRW process described earlier. The second method involves coating fiberglass containers, which hold the hazardous waste, by spraying-on or brushing-on a covering. The third method involves overpacking of a standard 55 gallon drum (which contains hazardous waste) with a welded polyethylene container (85 gal capacity). Figure 17 shows the three methods reviewed by the researchers. Method 3 is usually applicable to liquid wastes stored in the 55 gal drums and is a means of preventing leaks from the drums. Presumably it could be adapted to treat metal contaminated soils. However, the costs associated with this method of disposal would be high as wastes would have to be drummed first and subsequently overpacked. The authors² estimated that it would cost \$253/ton (1980 figures) assuming 80,000 55-gal drums are disposed/year.

3.15.2 Treatment effectiveness. Experimental data indicates that microencapsulation combined with macroencapsulation (TRW process) is an effective means of preventing metal contaminants from leaching into the receiving waters. Coupled with this is the added advantage of forming a mechanically strong block which makes it easy to dispose in a nonhazardous landfill. Studies have shown that the final encapsulated product can contain up to 94 percent of waste by weight. Macroencapsulation consisting solely of a secure outer container may have a lower effectiveness, since breach of the outer container may result in leakage.

3.15.3 Long-term stability/performance. Compared with chemical stabilization, macroencapsulation has a greater reliability in immobilizing metals in soils. This is because stabilization processes rely on the chemical affinity between the metal and the stabilization agent and is therefore susceptible to breakdown when soil conditions like pH change dramatically. Encapsulation on the other hand can be used on a number of types of wastes regardless of organic compound content and encapsulated wastes can withstand severe chemical and mechanical stresses.

3.15.4 Residuals treatment/disposal requirements. The encapsulated waste (unconfined or drummed) will have to be disposed in a landfill. Since these treated wastes exhibit excellent resistance to attack by leachate, they may be disposed in a nonhazardous facility. Disposal as a nonhazardous waste is most secure for the combined microencapsulation/macroencapsulation process.



Source: Reference [2]

FIGURE 17. Three schemes for encapsulating hazardous waste:
 Scheme I, resin fused onto surface of microencapsulated waste;
 scheme II, resin fused onto or sprayed onto fiberglass substrate
 holding containers of waste; scheme III, overpacking of 55-gal
 waste containers with welded plastic containers.



3.15.5 Flexibility. One of the distinct advantages of this process is that it may be used to treat a wide variety of wastes. Liquids in drums would have to be stabilized with a pozzolanic material, before being overpacked with HDPE, to comply with the recent RCRA rules prohibiting disposal of liquids in landfills. The process should be applicable to soils contaminated with metals and organics. Residues from organic treatment processes may also be treated.

3.15.6 Material throughput rate. It is anticipated that the process can be readily scaled up, although the microencapsulation/macroencapsulation version does present a difficult material handling application.

3.15.7 Potential disqualifiers. Preliminary indications are that the costs of disposal, especially when drums are overpacked with polyethylenes are high. Also, the process would involve excavation of soil and subsequent disposal of the encapsulated waste in a secure landfill. This is because the encapsulated waste may still be considered hazardous. Excavated areas would have to be backfilled with fresh soil. These additional actions would further increase the cost of implementation.

3.15.8 References.

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3.16 Microencapsulation.

3.16.1 Description. In this process, contaminant particles in solid or liquid waste are immobilized by encapsulation materials which create small scale encapsulation cells. Metals contaminated soils would be excavated and mixed with a polymeric substance in an extruder to form a product in which the contaminants are encased in a polymer matrix which is dispersed throughout the soil. Immobilizing materials (which form the matrix) may include polymers like polyethylene and other thermoplastics such as asphalt bitumen.

The SEALOSAFE process is a commercial full-scale method used to treat wastes. This process is operated under the trade name of STABLEX. Chappell and Willetts¹ have reviewed test data on independent tests to verify the manufacturer's claim that the process effectively isolates heavy metals. The process consists of first pretreating the waste to form a homogenized product. Pretreatment includes neutralization of acidic wastes by waste alkalis, reducing Cr^{6+} to Cr^{3+} by treating the waste with spent acid, and other processes as necessary. The pretreated waste is then thoroughly mixed with a monomer and subjected to polymerization to form a slurry which later (3 days) hardens to form a rock-like material. Leachability tests (under worst case conditions of grinding the product and subjecting it to an acid solution) conducted in the U.S., UK, and Japan showed that the leachate contained very low concentrations (<1 ppm total) of metal.¹ The permeability of the product is less than that of clays or concrete. The encapsulation materials are proprietary and have not been described.

Another immobilizing agent used to microencapsulate contaminants is asphalt. Brenner and Rugg² have investigated the effectiveness of using asphalt and asphalt/sulfur blends to encapsulate metals. In their experiments molten sulfur and liquefied asphalt were first mixed for 8 minutes to form an emulsion at a temperature between 285°F (141°C) and 300°F (149°C). This emulsion was then immediately mixed for 2 minutes with a preheated "simulated" waste like copper sulfate, at a temperature between 290°F (144°C) and 305°F (152°C). A variation in this process of mixing the solid waste in the asphalt and then mixing it with sulfur proved to be preferable because it yielded more uniform product. Their results showed that the best results, in terms of binding, were achieved when a ratio of 60 percent waste and 40 percent binder (asphalt and sulfur) are used. The tests also showed that product exhibited strong resistance to chemical and mechanical stresses. Minor problems with increased leachate due to partially encapsulated



particles were solved by applying a thin exterior coating of asphalt by hot spray or dipping. The authors emphasize that their findings are applicable only to the experimental wastes they used and that waste loading capacities may actually be higher for actual wastes used in a full scale process. They have also reported in 1982 that the estimated costs (excluding amortization) of treatment using a sulfur/asphalt blend would vary from \$41-45/ton for a 50 tons waste/week plant to \$42-44/ton for a 25 tons waste/week plant (waste solids = 60 percent by weight).² This cost does not include excavation and final use or disposal.

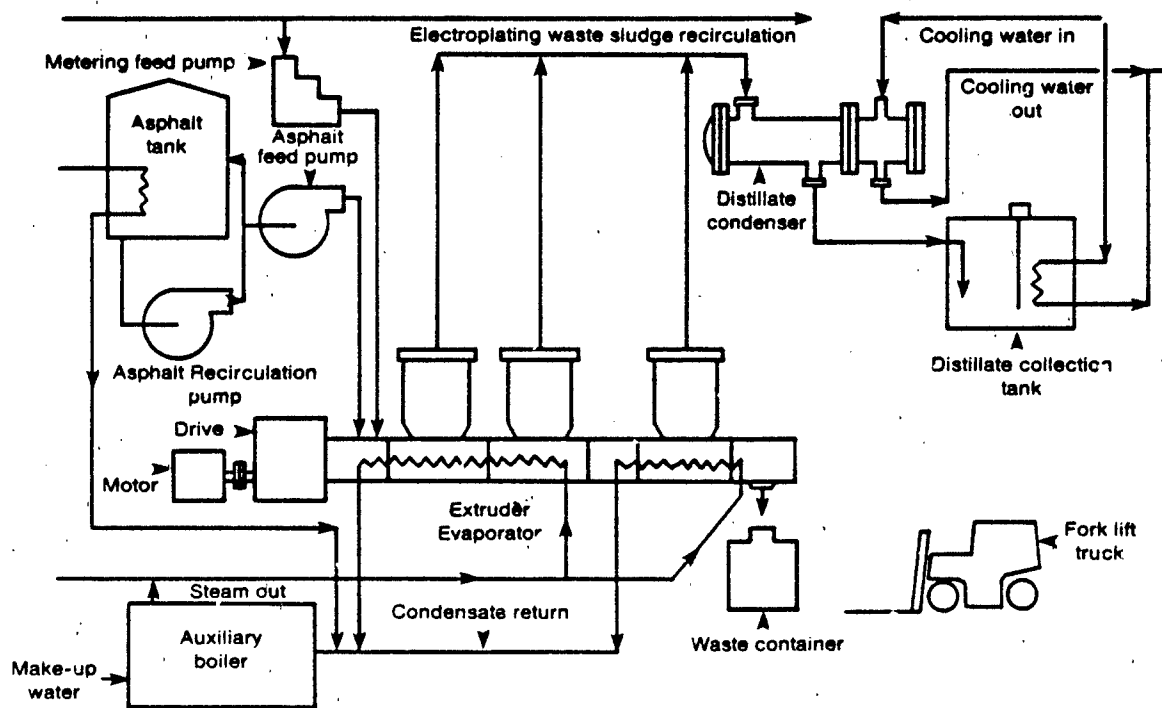
Brenner and Rugg² also state that this process has been implemented on a full-scale level and it is called the Volume Reduction and Solidification System (VRS). This full-scale VRS process is a nonchemical one and uses an extruder which simultaneously evaporates water from the waste while mixing it into the asphalt binder. The homogenized waste/asphalt mix is then discharged into containers where the mix cools down. Upon cooling, the volume of the waste/asphalt mix is reduced considerably. Figure 18 shows a process flow diagram for the VRS process.

Another process, described previously in Subsection 3.15 combines microencapsulation with macroencapsulation. The process, developed by Environmental Protection Polymers, was 1,2 polybutadiene and polyethylene to first coat the particles of soil or waste and then form a structural block. The block is then coated with high density polyethylene (macroencapsulated) before disposal.³

Another process involves the use of a organic polymer modified gypsum cement called Envirostone Cement, manufactured by U.S. Gypsum Company. This process is a hybrid variation or cement stabilization processes combining both inorganic cement with organic binders.⁴

3.16.2 Treatment effectiveness. Leachability and mechanical tests performed on both the STABLEX product and the asphalt/sulfur blend show they offer strong resistance to chemical attack and withstand mechanical stresses. Metals are effectively immobilized in the additive matrix which is dispersed through the waste. This process has been commercialized and operated at a full-scale level.

3.16.3 Long term stability/performance. Both the methods described previously produce very stable products which afford strong resistance to long term chemical and mechanical stresses. Metals are held in the additive matrix resulting in their long-term immobilization.



Source: Reference 2.

FIGURE 18. VRS process flow sheet for microencapsulation.



3.16.4 Residuals treatment/disposal requirements. The STABLEX product is a rock-like material which can be disposed in a nonhazardous facility. The VRS process yields a micro-encapsulated waste in disposal containers which can also be sent to a nonhazardous facility. There is some speculation that the products may be constructively reused in applications such as road backing. Emission controls on the extruder may be necessary if volatile pollutants (i.e., organic compounds) are present in the waste.

3.16.5 Flexibility. The process can also be used on liquid wastes and sludges. Residues from organic treatment processes can also be readily treated. Soils contaminated with organic wastes and metals may be treated together, but elevated processing temperatures may necessitate emission controls.

3.16.6 Material throughput rate. Full scale processes are presently feasible. Units with capacities of 25-ton/week and 50-ton/week have been suggested in the literature.

3.16.7 Potential disqualifiers. While this process does require extensive soil handling and processing at elevated temperatures, no serious disqualifiers are indicated. The stated cost would be increased by costs for soil and, if not backfilled on the original site, backfill with imported soil.

3.16.8 References.

1. Chappell, C.L. and S.L. Willetts, Journal of Hazardous Materials, 3 (1980) pp. 285-291, published by Elsevier Scientific Publishing Company, Amsterdam.
2. Brenner, W. and B. Rugg, "Exploratory Studies on the Encapsulation of Selected Hazardous Wastes With Sulfur - Asphalt Blends," Land Disposal of Hazardous Waste: Proceedings of the 8th Annual Research Symposium, held at Ft. Mitchell, Kentucky, on 8-10 March, 1982, conducted by Southwest Research Institute, San Antonio, Texas for U.S. EPA's Municipal Environmental Research Lab., Cincinnati, Ohio.
3. Lubowitz, H.R., and C.C. Wiles, "Management of Hazardous Waste by Unique Encapsulation Process," Land Disposal: Hazardous Waste Proceedings of the Seventh Annual Research Symposium, Philadelphia, Pennsylvania (16-18 March 1981), U.S. EPA, NTIS No. PB82-173022.



4. U.S. EPA, Handbook - Remedial Action at Waste Disposal Sites (Revised), EPA/625/6-85/006, p. 10-113 to 10-116.
5. Pojasek, R.B., Toxic and Hazardous Waste Disposal, Ann Arbor Science, Michigan, 1980.
6. Cullinane, M.J. and L.W. Jones, Technical Handbook for Stabilization/Solidification of Hazardous Waste. Prepared for U.S. EPA, Hazardous Waste Engineering Research Laboratory, Cincinnati, Ohio, 1985.
7. Doyle, R.D., Volume Reduction and Detoxification of Hazardous Wastes by Encapsulation in an Asphalt Binder. 35th Industrial Waste Conference, Perdue University, Ann Arbor Science Inc., Lafayette, Indiana, pp. 761-767, 1980.
8. Clark, D.E., P. Colombo, and R.M. Neilson, Jr., Solidification of Oils and Organic Liquids. BNL-5162. Prepared for: Brookhaven National Laboratory, U.S. DOE, pp. 25 1982.
9. U.S. EPA, Guide to the Disposal of Chemically Stabilized and Solidified Waste, SW-872. Office of Solid Waste and Emergency Response, Washington, DC, 1982.

3.17 Geologic isolation.

3.17.1 Description. Geologic isolation is an ultimate disposal method and not strictly speaking, a waste "treatment" technology. This method involves excavation of the contaminated soil, drumming it, and placement (of the drums) in secure, stable geologic formations which results in an isolation of the waste from the surrounding environment.

One proposed application of this technique is radioactive waste disposal in deep salt mines. This has been studied by the U.S. Department of Energy (DOE) for disposal of high level radioactive waste.

Another "more permanent" option for disposal is placement in the bed of the ocean. Drums containing wastes are placed in stable locations which contain unconsolidated clay beds. The drums would be placed well below the sea and be covered by the clay upon placement. In addition to the stability of the beds, clay has sorptive properties which would enable minor leaks to be absorbed by the bed materials. The lack of oxygen is known to prevent oxidation and biodegradation. This method is being used by European countries for disposing low-level radioactive wastes and has been studied by U.S. DOE.



Ocean dumping is being viewed with increased disfavor by the U.S. and other countries, as a means of waste disposal. The bad experience with the disposal of municipal sludge at the 12 mile site in the Atlantic Ocean has prompted efforts by the U.S. Congress to ban ocean disposal of wastes. Apart from degradation of the ocean beds by disposal, there is added uncertainty about the long-term effects of this process. While sea bed disposal does not have the same impact as ocean dumping of trash and sludge, it is likely to receive unfavorable consideration in the future.

While low-level radioactive wastes are expected to become nonhazardous in 10-100 years, metals may retain their hazardous properties indefinitely. Since sea bed stability is difficult to predict, the long term security of this approach may also be in doubt.

The cost for this technology is expected to be quite high, due to the problems of accessibility and disposal site development in addition to the costs for excavation, transportation and backfilling.

Soils with low metal concentrations and low leachability could potentially be dumped directly onto the ocean with little adverse effect at a significantly lower cost. This would likely encounter serious regulatory and institutional obstacles and is, therefore, considered infeasible.

3.17.2 Treatment effectiveness. This technology results in the removal of contaminants from the site and is therefore an effective means of remediating a metals contaminated site. The ability of salt domes to isolate material from the environment has been studied. Storage of petroleum gases and liquids in salt domes has been utilized, and some well known incidents of leakage have occurred. Storage of solids may be more successful, but careful site selection and development is clearly called for.

Sea bed disposal has been utilized successfully for low level radioactive waste disposal in Europe. Accidental release or improper placement during disposal operations may be more likely in deep sea operations, however.

3.17.3 Long-term stability/performance. The long-term effects of dumping sludge onto the ocean appear to be deleterious. Disposal of waste well under the sea bed in stable clay sediments may, however, provide long term secure storage/disposal. The ability to predict the duration of stability in deep sea beds is uncertain at this time.



Geologic isolation of radioactive wastes in deep salt-mines appears to be a stable long-term disposal option. Although leakage has occurred on certain installations for oil and gas storage, properly selected sites may provide indefinite secure disposal for solids.

3.17.4 Residual treatment/disposal requirements. This is not a "treatment" technique and does not yield any residues. The contaminated soil itself is disposed.

3.17.5 Flexibility. This method of disposal can be applied to a variety of wastes. Sludges and liquid wastes can be drummed and disposed. Wastes containing organics or residues from organic treatment processes can also be disposed.

3.17.6 Material throughput rate. Disposal rates may be adjusted upward based on the design of mine access ways for salt mine disposal. Deep sea excavating and material handling equipment may be increased in size and/or operated in parallel. Specific limitations on disposal rate are not available.

3.17.7 Potential disqualifiers. Potential disqualifiers include:

- (a) Ocean disposal, may not be an option that would be available because it may be legally or institutionally unacceptable.
- (b) There are a few salt dome burial sites which are under active consideration for radioactive waste disposal. This method may be excessively expensive for disposal of soils with very low metal contaminant concentrations.
- (c) While this technology may become available commercially or under the U.S. DOE program as a more secure disposal option, it does not constitute waste treatment.

3.17.3 References.

1. Bove, L.J., C.L. Cundall, W.P. Lambert, P.J. Marks, and J.F. Martino, Roy F. Weston, Inc., - Final Report - Removal of Contaminants From Soil - Phase I: Identification and evaluation of Technologies. (December 1983) Prepared for USATHAMA, MD-21010 Contract No. DAAK 1182-C-0017 Report No. DRXTH-TE-CR-83249.
2. Pojasek, R.B., ed, Toxic and Hazardous Waste Disposal, Ann Arbor Science, Inc., Michigan, 1980.



3.18 Secure landfill.

3.18.1 Description. This method is not a "treatment" technology but, is rather, an established commercial disposal technique. It is included here as the basis for comparison for treatment technologies. In addition, some treatment technologies may clean the soil of metals by producing a waste concentrate which requires subsequent treatment or disposal. The most likely disposal option is a secure landfill.

All contaminated soils would be removed from the soil using standard construction equipment like backhoes, draglines, dozers, etc. A "secure" landfill is a RCRA permitted facility which is designed and constructed to meet all applicable Federal, state and local laws and regulations. At a minimum these facilities now have double liners with a leachate collection and monitoring system to detect potential leakage and groundwater contamination. There are extensive EPA regulations for such hazardous waste disposal facilities to ensure that there is no harm to the environment.

Landfill liners may be constructed of chemically resistant polymeric membranes (e.g., high density polyethylene) and/or natural low permeability soils (clays). Another material suggested in the past as a separate liner or composite liner component is asphalt bitumen. The liner/cap system provides for surface runoff away from the fill and collection of any infiltration or waste originated leachate. The liner materials are designed to be resistant to chemical attack and must be carefully constructed and joined to prevent leakage. A typical double lined landfill design is presented in Figure 19.

A secure landfill can be constructed on-site, if the volume of waste warrants it, or can be shipped to an off-site landfill. Since dry metal contaminated soil can be expected to be quite compatible with most liner materials, co-disposal with more chemically active hazardous wastes (e.g., solvents, acids) would be undesirable.

The "off-site" disposal option has been used as a remedial action at many Superfund sites. In many instances only "hot spots" (high contamination areas) are excavated and disposed off-site. This reduces costs as soil/waste volumes that need to be disposed are lower. The overall cost of disposal depends on the type of waste, distance from site to landfill, volume of waste, etc. EPA estimated that landfilling costs are approximately \$240/ton for highly toxic wastes, \$120/ton for combustible wastes, \$80/ton for most industrial sludges and \$40-60/ton for municipal sludges. The cost for disposal of metal contaminated soil is expected to be in the low to middle range. However, landfill disposal costs are rising rapidly.

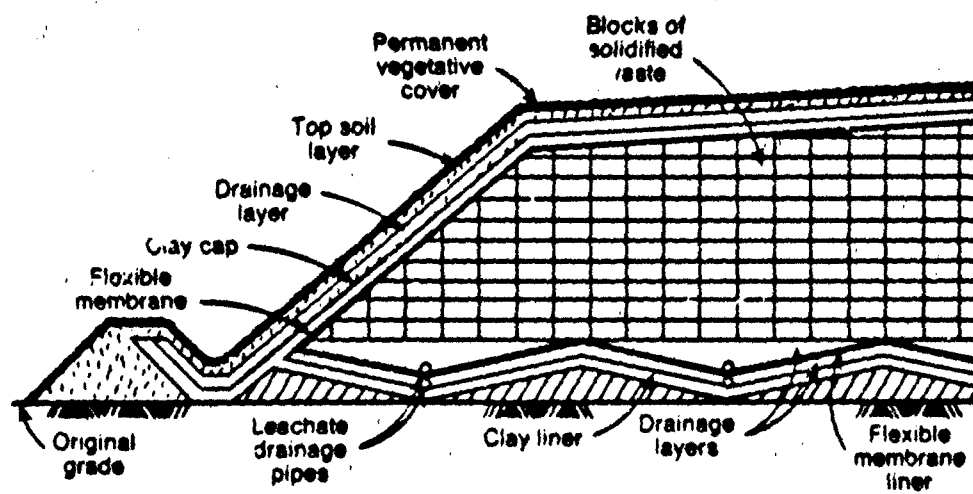


FIGURE 19. Cross-section of a secure landfill.



3.18.2 Treatment effectiveness. This option is an available and effective means of remedying a contamination problem. The source of contamination is removed from the site. The extent of removal e.g., up to background levels or EP toxicity levels is based upon an assessment of all the factors associated with the site cleanup. The disadvantage of this method is that the problem is transferred to another albeit more secure, site. Contaminant migration is controlled and performance can be readily monitored.

3.18.3 Long-term stability/performance. Well-designed landfills offer a safer long-term alternative for management of contaminated soils. Long-term stability and performance would depend on how the facility is operated and maintained over time. While landfill design has improved, the long-term performance with regard to natural forces (e.g., erosion and the potential for major events, such as earthquakes), chemical resistance, and physical strength may be a concern.

3.18.4 Residuals treatment/disposal requirements. Since the waste or contaminated soil itself is being disposed in a landfill, there is no other disposal of residues involved.

3.18.5 Flexibility. Landfills can accept a wide variety of wastes including sludges, residues and soils containing organic compounds. Again, EPA regulations specify treatment, storage and disposal requirements for all wastes. However, the RCRA reauthorization is likely to restrict landfilling of chlorinated organics and metals at high concentrations in the future.

3.18.6 Material throughput rate. Secure landfilling is the most widely available commercial technology and is best suited to large scale operation since maintenance and monitoring activities must be conducted regardless of size.

3.18.7 Potential disqualifiers. Potential disqualifiers include:

- (a) Limited availability of appropriate landfill capacity.
- (b) The RCRA reauthorization legislation may result in a future ban on landfilling wastes with high concentrations of metals.
- (c) Liability associated with future potential contamination or environmental problems at the landfill still rests with the generator.
- (d) Indefinite monitoring would be necessary to assure continued good performance. Future leakage could require remedial action.



3.18.8 References.

1. U.S. EPA Handbook: Remedial Action at Waste Disposal Sites (Revised) (October 1985). EPA/625/6-85/006.

3.19 In situ adsorption.

3.19.1 Description. Activated carbon or agricultural products could potentially be applied to soils in order to adsorb metals in situ. Adsorption of heavy metals by agricultural waste products and activated carbon was initially investigated for removal of heavy metals from wastewater. Activated carbon has been used extensively to treat wastewater for removal of organics. While rarely used exclusively for heavy metals removal, its performance in removing metals has been studied extensively.

Larsen and Schierup¹ experimented with straw, sawdust, and activated carbon for the possible removal of heavy metals from wastewater. Their experiments have shown that 1 gm of straw was able to adsorb from 4.3 to 15.2 mg of Zn, Cu, Pb, Ni and Cd. They also showed that efficiency of removal by the straw was generally best with the addition of CaCO_3 , a widely used metal precipitant. For a single batch application of straw and CaCO_3 to a 100 mg/l solution of metals, removal efficiencies of Zn, Cu, Ni and Cd remained below 50 percent, however. Pb removal was highest at 85 percent. Sawdust was less effective for all metals. Activated carbon performance was higher (up to 97.5 percent for Pb) but also generally unacceptable for removal of all metals. Column studies were conducted for continuous treatment of wastewater with barley straw. These showed that effective treatment (>99 percent) could be achieved for these metals utilizing a flow through column system. Acid regeneration or thermal destruction of the straw could further concentrate the metals for recovery or disposal. The lower removals exhibited under single stage batch conditions may be indicative of behavior of straw incorporated into the soil for in situ treatment, however.

Henderson et al² investigated adsorption of Hg, Cu, Ni, Cd and Zn onto peanut hulls and raw and aged barks. Again, these experiments were conducted to evaluate the feasibility of removing metals from wastewater using these natural waste products. Their data showed that up to 80 percent removal of Cu was achieved in batch tests using smaller particle size peanut hulls, but, again, removal of other metals remained below 60 percent.



Application of the above adsorption methods to the removal of metals from soils was a concept suggested as a potential treatment of metals contaminated soil in a study conducted for U.S. EPA.³ The technique would involve tilling the land to incorporate adsorbent materials, such as agricultural waste products and activated carbon, into the soil. Metals would be adsorbed onto these materials, thereby reducing their mobility and threat to the environment. The obvious advantage of using agricultural waste products is that they are very inexpensive (when compared to activated carbon). It is common practice to use agricultural products and by-products as soil conditioners (e.g., manures, composts, etc.).⁴ Sewage sludge has also been used as a soil conditioner and a source of fertilizer. However, using sewage sludge as a means of adsorbing metals would prove to be counter-productive because the sludge itself may contain large amounts of metals.

3.19.2 Treatment effectiveness. There are no specific studies on the application of this technique for removing metals from soils. Studies on the treatment of wastewater indicate that a single stage batch treatment (such as in situ soil treatment) may not be adequate to prevent migration of mobile metals. Other factors which could adversely affect adsorption capacity in soils include the presence of competing ions and chelating agents, low pH and high ionic strength.

Theoretically, this method should be able to immobilize a portion of the metals in soil by adsorption. However, organic materials, such as agricultural waste and activated carbon, are subject to microbial degradation and this degradation may result in the subsequent re-release of immobilized metals.⁵ Depending upon the type of organic product or byproduct used, nitrate levels in the groundwater may increase as a result of microbial degradation.

3.19.3 Long-term stability/performance. While activated carbon may be more stable than agricultural products, in either case the phenomenon of mineralization (microbial degradation) causing the release of the sorbed metals makes this process effective only over the short-term. Similarly, adsorption is also dependent on maintaining nearly neutral soil pH, necessitating long-term monitoring and soil neutralization. Therefore, in order to maintain initial performance long-term, repeated applications of both the organic material and liming will be necessary.



3.19.4 Residuals treatment/disposal requirements. One advantage of this process is that there are no residuals to be disposed since the treatment occurs in situ.

3.19.5 Flexibility. While there have been only a few experiments to show that agricultural waste materials may be used to adsorb metals from wastewater. Several studies have shown that agricultural products can immobilize organic chemicals, particularly pesticides, in soils.³ Likewise, activated carbon has been extensively used in wastewater treatment to remove organics and is rarely used for removal of heavy metals alone.

Wastes containing both organics and metals may present a problem, however. Since both of them are sorbable and organics are preferentially adsorbed by both activated carbon and agricultural products, metal adsorption may be decreased.

3.19.6 Material throughput rate. The incorporation of organic adsorbents into the soil can be readily accomplished using standard agricultural machinery. Therefore, a high rate of soil treatment is anticipated.

3.19.7 Potential disqualifiers. Potential disqualifiers include:

- (a) The ability of the process to immobilize metals in soil has not been demonstrated or tested. Extensive experimental and pilot-scale work remains to be done before applying the process on a full scale level. This would delay the availability of the process.
- (b) The performance of this technology applied to wastewater in batch studies indicates that mediocre performance can be expected in application to soils.
- (c) The long-term stability of the process is in question. It would require extensive site management because of the repeated applications of the organic materials, liming etc. In addition, site management in the form of diking etc. would be necessary as tilled soil is susceptible to erosion. Long-term monitoring to ensure that there has been no off-site migration of metals would be necessary.
- (d) Due to the above factors and because organics tend to alter soil properties like water holding capacity, bulk density etc, land use would be restricted.

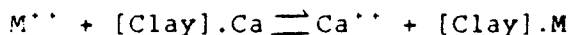
3.19.8 References.

1. Larsen, V.J. and H.H. Schierup, J. Environ. Quality, Vol. 10, No. 2, (1981) pp. 188-193.
2. Henderson, R.W., D.S. Andrews, G.R. Lightsey, and N.A. Poonawala, Bulletin of Environmental Contamination and Toxicology, Vol. 17, No. 3 (1977) pp. 355-359.
3. U.S. EPA - Review of In-Place Treatment Techniques for Contaminated Surface Soils - Volume 1, Technical Evaluation, EPA-540/2-84-002a (September 1984) pp. 40-58.

3.20 In situ ion exchange.

3.20.1 Description. The ion exchange process has been widely used to treat metal contaminated wastewaters. The basic principle of this process is that metal ions which are in solution can be exchanged with ions which are bound to a suitable medium, usually a synthetic organic resin. Clay and zeolites also exhibit ion exchange properties and may be utilized in situ. While the applicability of ion exchange to treat metal contaminated wastewaters has been demonstrated, its application to treatment of metal contaminated soils is at the conceptual stage. This concept would involve incorporation of the zeolites and clays into the soil by tilling. Runoff and sedimentation control measures would be necessary because tilled sites are susceptible to erosion. The ability of these ion exchangers to remove metals is affected by different factors like 1. pH, 2. competing cations, 3. presence of complexing agents, 4. soil solution ionic strength, and 5. type of anions.

Clays have an affinity for metal cations and exchange calcium ions for them. This process has been characterized as follows:



Clays have been found to attenuate the migration of metals through soils but little information is available on application of clay to soils to immobilize metals. Smeulders et al¹ have studied the in situ immobilization of metals on clay by first complexing them with tetraethylenepentamine (tetren). They have shown that the ion exchange behavior of heavy metals



like Cu, Zn, Ni, Cd is very strongly influenced by the tetren complex. They have also shown that clays have a greatly increased affinity for the tetren-complexed heavy metals. Based on these results one may conclude that a process which incorporates clay and tetren into the soil would result in more effective immobilization by ion exchange compared to using just clay. Soils containing clay may be treated at a lower cost since commercial clay addition may not be necessary.

Synthetic ion exchange resins have long been utilized for metals removal from low strength industrial wastewater streams. The resin beads are stable polymerized hydrocarbons with various ionic functional groups which can exchange innocuous ions (i.e., Ca^{+2} , Cl^-) for ions in solution. Application of ion exchange resin beads to the soils has been suggested for pesticides but no experiments have been conducted. In situ application of resins has several potential disadvantages, including poor contact between beads and soil, high cost, and competition for exchange sites with naturally occurring ions.

Zeolites are natural hydrated aluminosilicate crystals with a typical chemical formula of $\text{Na}_2\text{Al}_2\text{Si}_4\text{O}_{12}$. They exhibit a selectivity pattern for certain metal ions (Cd, Cu, Pb, Zn) which is different from other ion exchange media, and, in some ways, superior. Zeolites are relatively stable over a wide pH range from 6-12, but degrade when the pH is below 4-5, they should be applied mainly to neutral or alkaline soils or soil pH should be maintained by regular liming. High pH may have the added benefit of causing metals precipitation.¹

While natural zeolites are widely utilized in industrial applications for water treatment (molecular sieves) and for agricultural applications (retention of ammonium and potassium), they have not been studied for in-situ soil treatment. They do represent a less expensive alternative to ion exchange resins.

3.20.2 Treatment effectiveness. Natural zeolites and ion exchange resins have been found to be effective in removing heavy metals from water in full scale applications. This process is sensitive to pH, and the presence of competing ions, however. No data is available for direct application to soils.



The research on enhancing immobilization of metals on clays by the addition of a complexing agent (tetren) appears to be promising. Experiments reduced the soluble metal levels as much as two orders of magnitude as compared with clay alone. The improved performance is particularly exhibited with higher metal ion concentrations. Concentrations in solution for Cu were below 1 ppm with a clay-tetren loading of 1,000 ppm of Cu.⁴ The process may be less effective for lower concentrations of metals and where high levels of cations (Na^+ , Ca^{+2} , Fe^{+2}) may interfere with the capture of heavy metals.

3.20.3 Long-term stability/performance. There have been no studies to determine the long-term stability of this process and its ability to immobilize metals in soil. If zeolites are used then long-term site management including liming and maintenance of erosion controls would be necessary. Similar potential impacts may be expected for resins or tetren-clay mixtures.

3.20.4 Residuals treatment/disposal requirements. This is an in situ process and there are no residuals to be disposed since the immobilized metals stay within the soil.

3.20.5 Flexibility. The clay-tetren process and ion exchange resin process may be also be used to treat sites contaminated with certain organics along with metals if the organic cations are sorbed by clay. Zeolites, on the other hand, are only for treatment of heavy metals. The ability of the resin and zeolite processes to treat metal contaminated liquid wastes at low concentrations are well established but successful treatment of high concentration sludges is unlikely. Treatment of residues from organic treatment processes may be feasible, but on-site processing may be more appropriate than in situ processing.

3.20.6 Material throughput rate. The in situ process would utilize common agricultural machinery capable of treating large soil surface areas.

3.20.7 Potential disqualifiers. Potential disqualifiers include:

- (a) The process, as applied to soils, is still in a conceptual stage. Therefore, there is little information available on treatment effectiveness, process parameters, cost etc., with exception of the clay-tetren process.

- (b) The long-term stability of the process is questionable as ion-exchange media are typically sensitive to pH.
- (c) The process may be less effective in sites where heavy metals are present in trace amounts and when excessive amounts of ions like Na^+ , Ca^{+2} , Fe^{+2} , etc. are present in the soil.

3.20.8 References.

1. U.S. EPA - Review of In-Place Treatment Techniques for Contaminated Surface Soils. Volume 1: Technical Evaluation (September 1984) EPA-540/2-84-003a.
2. Blount, E.A., Electroplating and Metal Finishing, Vol. 28 No. 3, March 1975, pp. 11-14.
3. Gott, R.D., American Mining Congress Journal, Vol. 64, No. 4., April 1978, pp. 28-34.
4. Smeulders, F., A. Maes, J. Sinnaeve, and A. Cremers, Plant and Soil, 70, pp. 37-47 (1983).
5. Sherman J.D., Ion Exchange Separation With Molecular Sieve Zeolites. In Adsorption and Ion Exchange Separation, Sherman, J.D. (ed), AIChE Symposium Series No. 179:98-116.

3.21 On-site ion exchange.

3.21.1 Description. Ion exchange has been proposed by Sengupta¹ in a recent theoretical paper as a technique for metal removal from waste ash or sludges which contains low concentrations of metals. The waste would be slurried in water and mixed with ion exchange resin beads. Although metal solubilities in water may be low, the selection of a resin with a high affinity and selectivity for the metal would result in removal of the metal compounds from solution and a continued driving force for solubilizing metals from the waste. Preliminary laboratory studies showed that most lead carbonate was removed from a slurry within two hours.

Following completion of slurry transfer, the slurried waste is drained while the resin beads are retained by a basket strainer for subsequent regeneration. The slurry can be dewatered and disposed as a nonhazardous waste. A process schematic is shown in Figure 20.

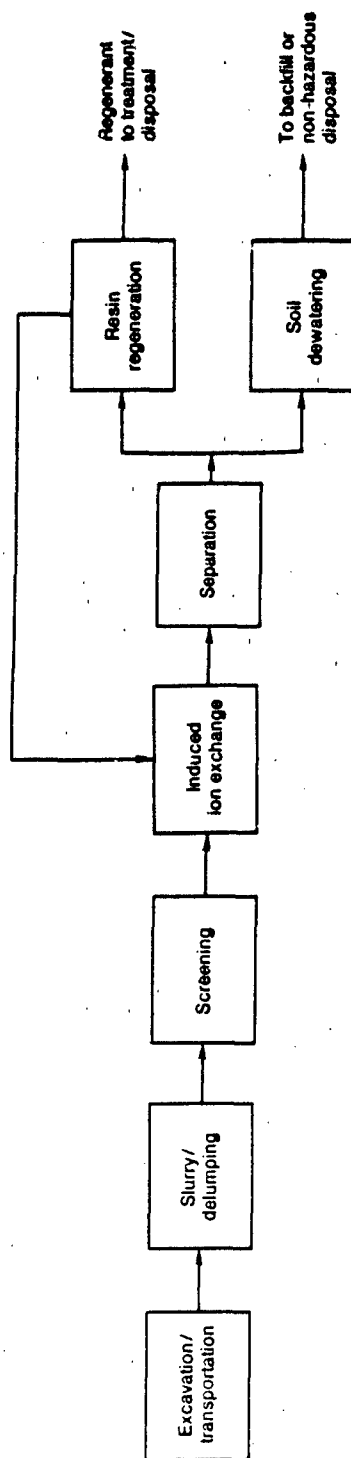


FIGURE 20. On-site ion exchange process schematic.



The application of this technology to contaminated soils would necessitate a modification of material handling to include prescreening soil particles or devising an alternative slurry/resin separation technique (e.g., flotation).

Significant constraints on the use of this technology include the competition of other soil cations which may be present at much higher levels, and the limited capacity of ion exchange resins. These factors may result in the production of a low concentration regeneration solution which requires further treatment/disposal.

3.21.2 Treatment effectiveness. Ion exchange resins have been used successfully to remove metals from wastewater to extremely low levels. If adequate dissolution of metal compounds can be sustained throughout treatment, low concentrations can be achieved in the treated soil. Since the effectiveness depends on concentrations, metal species, resin characteristics, conjugate ion or molecule concentrations, and competing ions, its effectiveness must be tested for each soil/metal matrix.

Another consideration in assessing the effectiveness of the technology is the form of the metal containing residual stream. If resin loading is inadequate for the particular soil/metal input, the volume of metal concentrate solution may be too high relative to alternative techniques. (e.g., extraction with acids or chelating agents).

3.21.3 Long-term stability/performance. Since metals are removed from the soil, if short-term performance is acceptable, then long-term performance is assured.

3.21.4 Residuals treatment/disposal requirements. The concentrated regeneration solution and lower concentration rinse solutions require further treatment or disposal. These solutions may be treated by conventional chemical precipitation techniques (e.g., lime, sulfide, etc) or with alternative recovery techniques (e.g., electrodeposition). The more cost effective precipitation process will result in a concentrated sludge for further treatment or probable disposal as a hazardous waste.

3.21.5 Flexibility. Significant destruction or capture of organics is not expected. Treatment of soils contaminated with organics may prove difficult if significant solubilization occurs in the slurry filtrate or if ion exchange fouling results. Residues from organic treatment processes may be treated. High concentration sludges (or soils) would not be efficiently treated due to the limited capacity of ion exchange resins.



3.21.6 Material throughput rate. The process includes numerous processing and separation steps but should be readily scaled up with available processing equipment.

3.21.7 Potential disqualifiers. Potential disqualifiers include:

- (a) As metal concentrations and competitive ion concentrations increase, the volume of regenerant increases. Under these circumstances, the objective of this treatment (to create a low volume concentrated metal bearing stream while treating soil) may not be met.
- (b) Further processing and residuals disposal will be necessary.

3.21.8 References.

1. Sengupta, A.K., Detoxifying Metal-Contaminated Solid Wastes by Induced Ion Exchange - a Theoretical Evaluation. Proceedings of the Specialty Conference in Environmental Engineering, ASCE, pp. 306-313, March 1986.



4. PRELIMINARY SCREENING EVALUATION

The 21 technologies identified and described in Section 3 were evaluated in two stages. The first level feasibility screening evaluation was designed to identify 2 to 3 of the most promising technologies for further evaluation. The screening process used a few key criteria which gauge the technical feasibility of each technology. This section describes the feasibility screening criteria, the evaluation procedures and the results of this first level evaluation.

4.1 Screening criteria. The feasibility screening utilized the following criteria to evaluate the technologies:

- (a) Treatment effectiveness - Ability to remove metals or render the substrate nonhazardous (per EP Toxicity criteria) to meet regulatory or clean-up objectives.
- (b) Long-term stability/performance - Assess the permanence of the treatment performance in the long-term. The effectiveness of the treatment process in rendering the soil nonhazardous may be impacted by long-term environmental conditions (i.e., weathering, infiltration, pH, etc.).
- (c) Residual treatment/disposal requirements - If potentially hazardous residuals may be formed, additional treatment processes or secure disposal will be required. If residuals treatment is not addressed, it could require further development. If residuals disposal is necessary, this negatively impacts future risk and liability.
- (d) Flexibility - Ability to treat various soil/site types, other waste streams, to treat for organics and metals, to be linked to other organic treatment processes, or to handle materials with variable physical consistency.
- (e) Material throughput rate - Ability to process large quantities of soil or anticipated ability to scale up to meet this objective.
- (f) Potential disqualifiers - Evaluate potential fatal flaws to determine if any would prevent technology development or implementation.

The criteria were selected as the most important criteria which address technical feasibility (i.e., applicability and achievement of treatment and project goals). They were selected from a more comprehensive listing of criteria developed for the Comprehensive Technology Evaluation (see Section 6). The Feasibility Screening criteria are listed in Table 8 along with their relative weighting factors, also taken from Section 6 (see Table 17).



TABLE 8. PRELIMINARY EVALUATION CRITERIA AND RATING FACTORS

Criterion	Rating factor
1. Treatment effectiveness	4
2. Long-term stability/performance	3
3. Residuals management/disposal requirements	3
4. Flexibility	2
5. Material throughput	2
6. Potential for disqualification	nonnumerical consideration of known or potential fatal flaws which would prevent implementation

Assignment of rating factor taken from Table 17.



4.2 Screening process. The Feasibility Screening was conducted by a multidisciplinary Technical Review Committee. Reviewers were provided with an interim report which gave a summary of the information gathered on each technology, including a description, preliminary design concepts and an assessment of the ability to meet the evaluation criteria for the Feasibility Screening. The interim report was distributed on 26 August 1986. After the committee reviewed the report and made preliminary technology evaluations, a meeting was held on 3 September 1986 at WESTON's West Chester office. The purpose of the meeting was to provide a forum for exchange of views on advantages and disadvantages of each technology. The resolution of conflicting views would provide a consensus evaluation, avoiding the subjective bias inherent in a project team evaluation.

The technical review committee consisted of the following people:

Evaluator number	Name	Affiliation
1	G. Anastos	Environmental Engineer Roy F. Weston, Inc.
2	M. Corbin	Mechanical Engineer Roy F. Weston, Inc.
3	J. Petura	Chemical Engineer Roy F. Weston, Inc.
4	P. Siebert	Air Resources Roy F. Weston, Inc.
5	W. Sitman	Environmental Engineer Roy F. Weston, Inc.
6	P. Puglionesi	Chemical Engineer Roy F. Weston, Inc.



The reviewers were given rating sheets (for each technology) in which the Feasibility Screening and rating factors were listed. The form given to the evaluators is presented in Table 9. They were asked to assign numerical scores ranging from 1 to 5 for each of the rating criteria with the exception of the potential disqualifiers criterion which was nonnumerical. The numerical scores were to be multiplied by their respective weighting factors and the products were added to yield the total numerical score for each technology. The evaluators were also asked to make comments (on the sheets) which would explain the basis for their scores.

At the 3 September 1986 meeting, the salient features of each of the technologies were first presented by WESTON staff engineers. This presentation was followed by a technical discussion during which the advantages and disadvantages of the technologies, as identified by each evaluator, were highlighted. The ratings assigned by each evaluator were also discussed. The discussion culminated in a general consensus being reached on the numerical scores, for each of the rating criteria, for every technology. A consensus was also reached on the potential disqualifiers. These consensus scores and findings were recorded on separate rating sheets, supplementing the rating results from individual evaluators.

4.3 Results and conclusions. Table 10 is a summary of the Feasibility Screening results. It contains the total numerical scores for each of the technologies assigned by each evaluator. These numerical scores were averaged by technology and evaluator. The table also contains the consensus numerical scores which are slightly different from the technology average for all reviewers. Since the technology averages were calculated using scores which were given by the evaluators before the review meeting, and the consensus scores were based on interaction and consensus reached during the technical review meeting, the consensus scores were utilized to rank the technologies. Technologies were evaluated by professionals with different backgrounds and biases; therefore, the consensus ratings represent complete and balanced evaluations of the various processes.

The objective of the feasibility screening process was to select 2 or 3 technologies which had a good probability of success. These technologies would then be studied further and detailed concept designs, R&D considerations, and costs would be developed.



TABLE 9. TECHNOLOGY EVALUATION FORM

Treatment technology:

Evaluator:

Criterion	Rating factor (RF)	Numerical score (NS)	RF x NS	Comments
1. Treatment effectiveness	4			
2. Long term stability performance	3			
3. Residuals treatment/disposal requirements	3			
4. Flexibility	2			
5. Materials throughput rate	2			
Total				
6. Potential disqualifiers/fatal flaws (nonnumerical)			Yes No N/A	
- Inherently unsafe				
- Uncontrollable environmental risk of mobilization				
- Uncontrollable air emissions				
- Exceedingly expensive				
- Exceedingly complex materials handling, operations or maintenance				

Additional comments:



TABLE 10. SUMMARY OF THE FEASIBILITY SCREENING RESULTS*

Technology	Evaluator number						Tech- nology average	Con- sensus scores
	1	2	3	4	5	6		
1. In situ vitrification	53	46	57	52	47	58	52.2	51
2. On-site vitrification	56	52	58	59	51	61	56.2	57.5
3. On-site plasma arc	32	52	43.5	37	30	45	39.9	37
4. HTFW reactor	28	31	31.5	46	28	40	34.0	33
5. Roasting	53	56	56.5	50.5	50	58	54.0	54.5
6. Chloride volatili- zation	43	43	40	41	34	42	40.5	44.5
7. HGMS	34	33.5	39	34	27	37	34.0	32.5
8. On-site precipitation	23.5	34	22	30	24	36	28.3	26.5
9. In situ precipitation	16	34	25.5	23	29	32	26.6	22.5
10. In situ precipitation/ vap. phase	20	41	33	22	25	37	29.7	30.5
11. On-site extraction	40	36	45	45	32	47	40.8	40
12. In situ extraction	44	39	40	37	30	42	32.2	39.5
13. Vegetative uptake	27	20	25	32	22	25	25.2	20

*Table is continued on next page.



TABLE 10. (CONTINUED)

Technology	Evaluator number						Tech nology average	Con- sensus scores
	1	2	3	4	5	6		
14. Stabilization (admixing)	53.5	50.5	55	54	46	57	52.7	54
15. Macroencap- sulation	32	37	43	43	49	42	41.0	41
16. Microencap- sulation	56	51	56	54	51	54	53.7	55
16a. In situ microencap- sulation	---	---	---	---	---	---	---	46
17. Geologic isolation	49	34	49	41	46	49	44.7	49
18. Secure landfill	40	34	53	47	48	53	45.8	48
19. In situ adsorption	32	37	35	34	31	33	33.7	36
20. In situ ion exchange	31	40	40	32	32	42	36.2	38
21. On-site ion exchange	<u>34</u>	<u>38</u>	<u>31.5</u>	<u>43</u>	<u>31</u>	<u>37</u>	<u>35.8</u>	<u>34.5</u>
Evaluator average	40.0	40.0	41.8	40.8	36.3	44.1	39.9	40.5



It should be noted that while technical summaries on 21 technologies were prepared by WESTON staff in advance of the review meeting, the additional technology of in situ microencapsulation was developed during the technical review meeting. A consensus was arrived at on the ratings for this technology; there were no individual scores.

The following is a tabulation of the top 11 technologies, based on their consensus scores:

Rank	Technology	Score
1.	On-site vitrification	57-1/2
2.	Microencapsulation	55
3.	Roasting	54-1/2
4.	Stabilization (admixing)	54
5.	In situ vitrification	51
6.	Geologic isolation	49
7.	Secure Landfill	48
8.	In situ microencapsulation	46
9.	Chloride volatilization	44-1/2
10.	Macroencapsulation	41
11.	On-site extraction	40

Preliminary consensus rankings were discussed at the meeting. During the course of this discussion, it was recommended that Geologic Isolation and Secure Landfill should not be considered any further because they were not treatment "technologies" per se. Macroencapsulation was ruled out because of fatal flaws which included high costs and institutional concerns (e.g., soil is not rendered nonhazardous by macroencapsulation alone and long-term containment and monitoring must be provided).

It was suggested that although roasting was far more attractive than chloride volatilization they might be combined and studied in a single technology development program. However, further technology evaluation and cost estimation should focus on roasting, the more promising technology.

In situ microencapsulation was ruled out because it had a lower probability of success compared to microencapsulation and also had a higher potential for contaminating groundwater. It was suggested that microencapsulation could be combined with stabilization (admixing) and studied as one technology. Stabilization (admixing) has become extensively commercialized



in recent years, however, and its application to a remedial action site can be evaluated on the basis of bench testing and historical information for each application. Because it is considered a proven technology with a substantial performance track record, additional R&D for the stabilization technology was not considered to be justified. Therefore, further evaluation and cost estimation should focus on microencapsulation, the technology which is more likely to require further development effort prior to implementation.

USATHAMA indicated that both vitrification technologies (in situ and on-site) were being studied as part of the cleanup for the Rocky Mountain Arsenal. Although these were rated high, the need for a separate R&D program for these technologies was not considered justified at this time, considering the present ongoing work. Consequently, on-site extraction was recommended as a candidate for further study despite it having a lower rating than the vitrification technologies. On-site extraction was rated lower primarily on the basis of uncertainty of achieving the required treatment performance and the need for subsequent processing steps for the extract solution. However, the potential for efficient cost-effective processing of metal contaminated soils makes this technology worthy of further evaluation.

In summary, the following technologies were selected for further detailed evaluation:

- (a) Microencapsulation.
- (b) Roasting.
- (c) On-site extraction.



5. CONCEPTUAL DESIGN

The conceptual designs for the three technologies selected for a more detailed evaluation are further developed in this section. This information will be used in the second level technical evaluation conducted in Section 6.

The design basis and assumptions used for the conceptual designs, representing hypothetical Installation Restoration (IR) applications, were developed from the USATHAMA IR data base and previous studies for USATHAMA. These hypothetical applications provide a basis for developing process flow sheets, and treatment cost projections. The conceptual designs include technology descriptions, process concept selection, process flow sheets and cost estimates. A discussion of development requirements is also included for each technology.

5.1 Basis for conceptual design evaluation

5.1.1 Hypothetical applications. Since there are numerous potential Army IR sites at various locations in the country with differing soil and contaminant characteristics, a hypothetical site was considered to compare the three chosen technologies on the same basis. A similar approach has been used by WESTON in a study for USATHAMA entitled "Installation Restoration General Environmental Technology Development Task 11, Pilot Investigation of Low Temperature Thermal Stripping of Volatile Organic Compounds (VOC's) from Soil" (Report No. AMXTH-TE-CR-86074) and a subsequent Draft Technical Report, June 1986. The following assumptions/ conditions were used in developing and comparing the concept designs for the three technologies:

- (a) Two separate quantities of soil to be processed, representing a range of sites, would be investigated as follows:
 - Site 1 - 10,000 tons
 - Site 2 - 100,000 tons
- (b) Soil type: Silty clay with sand.
- (c) Soil density prior to excavation:
 - Average 100 lb/cu ft
 - Range 90-110 lb/cu ft
- (d) Soil bulk density after excavation:
 - Average 75 lb/cu ft
 - Range 65-85 lb/cu ft
- (e) Soil moisture content:
 - Average - 20 percent
 - Range - 15-30 percent
- (f) Soil is assumed to be contaminated only with the following metals and concentrations:



<u>Metal</u>	<u>Concentration (as total metal)</u>
Chromium	Range 1 - 3,000 mg/kg Average 1,500 mg/kg
Lead	Range 1 - 5,000 mg/kg Average 2,500 mg/kg
Cadmium	Range 0 - 500 mg/kg Average 250 mg/kg

This represents the range of concentrations for chromium, lead, and cadmium found on the six installations previously identified in Section 2. Since detailed information on concentration distributions over the contaminated soil areas was not available, the average of the range was selected to represent the design basis average. It must be noted that metal concentrations may be important in the design and operation of the on-site extraction process. The other two technologies should be relatively insensitive to the input soil metal concentrations.

- (a) Time required for cleanup to be completed was assumed to be 1 year from startup. This is applicable to both the quantities of soil (i.e., 10,000 tons and 100,000 tons).
- (b) While a mobile unit may be most desirable, it would be difficult to cost all three technologies on this basis, given the varying levels of development. For the purposes of comparison, costs were developed based on a permanently installed on-site process unit. However, the potential for design of a mobile or reuseable/relocatable process unit was assessed. It should be noted that an on-site unit could either be operated to treat the soil at one site alone or to serve as a central processing facility. In order to eliminate siting considerations, costs for the on-site unit were based on the boundary limits of the installation. Factors which distinguish a centralized facility from a single site unit, such as utility connections and soil transportation costs were not calculated.
- (c) Potential applications of soil treatment for metals may also require treatment for volatile organics or explosives. Likewise, these technologies could potentially be applied to metal bearing sludges. Since the principal purpose of the evaluation is to compare technologies prior to development, evaluations of subalternatives and options should be limited at this



stage. Therefore, the primary basis for concept design and technology comparison is an application with only metal contaminants. Some consideration will be given to alternative process configurations and treatment costs on a less rigorous basis.

- (d) Assumed labor and energy rates were used to calculate the operating costs for the three technologies. These rates represent national averages applicable to the hypothetical site considered in the designs. It must be noted that since the total project time is one year, the capital and operating costs were added to obtain the total annual project cost.

5.1.2 Performance objectives. Section 2 contains a discussion about the applicable guidelines/criteria and the metal concentration targets that a technology would be expected to meet. On 8 November 1986, new EPA regulations on Toxicity Characteristic Leaching Procedure (TCLP) went into effect. The regulations specified new limits for solvents and dioxins. For now, EP toxicity limits will still be used to determine if wastes with metals are hazardous. There are indications that the EPA may revise these metal limits in the future. Therefore, a technology which completely removes or immobilizes the metals in the soil would be preferable compared to one that does not. Such a technology would not be affected by changes in the EP Toxicity levels or by strict site remediation requirements. Site remediation standards that would determine minimum soil clean-up levels for metals on all sites currently do not exist. The maximum requirement expected is cleanup to background levels. Clean-up levels are typically determined by site-specific assessments of the potential for migration and receptor exposure. Since there are no generally applicable site remediation standards, it is suggested that the EPA Extraction Procedure (EP) Toxicity limits for defining hazardous waste characteristics be used as a minimum treatment objective.

5.1.3 Assumptions. Regarding cost estimates. Preliminary concept level cost estimates were developed for all the three technologies--microencapsulation, roasting, and on-site extraction. These estimates are presented in the form of tables in the following sections for each of these technologies.

Since the concept designs were not based on a specific site, the following average labor rates for a generic site were used for all the three technologies.



Job Classification	Hourly Rate (\$/hr)
Site Leader	30
Site Safety	20
Loader/Equipment Operators	18
Transport Equipment Operators	18
Contract Mechanic/Electrician	20
Administrative Support	10

These labor rates were obtained from a previous WESTON study for USATHAMA on the removal of volatile organic compounds (VOC's) from soil, using the Low Temperature Thermal Stripper (LTTs) unit ("Economic Evaluation of Alternative Options for Low Temperature Thermal Stripping of Volatile Organic Compounds from Soil," Draft Technical Report, June 1986).

In addition to the specific equipment listed for each technology in the following sections, certain other support, soil handling, and transportation equipment would be needed to implement all three technologies. This equipment would be readily available on a rental basis at each site.

The following is a list of the support, soil handling, and transportation equipment and their rental charges which were used in calculating the O&M costs for each of the technologies:

Description	Rate (\$/yr)
1. Front-End Loaders (1 cu yd bucket 60 cu yd/ hr maximum production rate)	80,000
2. Dump truck (16 ton maximum capacity)	30,000
3. Trailers (office, decon, storage)	12,000
4. Sanitary Facilities	2,000
5. Safety Equipment	5,000



Minor utility costs such as for water supply and smaller electricity consuming equipment, were not calculated for the technologies. However, fuel and electricity costs which were significant in the processes were included in the cost estimates. The following unit costs were assumed (these were applied to all the three technologies):

Description	Unit Cost
1. Electricity	\$.06/kwh
2. Fuel oil	\$7/10 ⁶ Btu
3. Diesel fuel	\$1.20/gal

Costs for certain raw materials which are specific to each technology are discussed separately in the subsequent sections.

As indicated previously, the cost figures in Subsections 5.2, 5.3, and 5.4 were conceptual level estimates for each process. These estimates did not account for the following costs:

- (a) Any RCRA Part B permits that may be required on a particular site.
- (b) Remedial Investigations/Feasibility Studies (RI/FS) which may have to be performed.
- (c) Profits which a private contractor might charge.
- (d) Insurance requirements for a private contractor.
- (e) Salvage value of the equipment.
- (f) Process development including lab and pilot studies and engineering efforts for process optimization and final conceptual design.
- (g) Site-specific cost impacts due to transportation of soil, long distances for utility tie-in, etc.

In addition to the above exclusions, there were certain costs specific to a given technology which would not be estimated at this time. The sections on each technology discuss these specific exclusions.

5.2 Microencapsulation

5.2.1 Discussion. In this process, waste materials (solid or liquid) or contaminated soils are immobilized by mixing them with an organic based binder material to create small scale encapsulation cells. Metals contaminated soils would be excavated and mixed with a polymeric substance in an extruder to form a product which hardens upon cooling. The contaminants



are physically encased in a polymer matrix which is dispersed throughout the soil. Materials which can be used to form the immobilizing polymer matrix include thermoplastic polymers like polyethylene polyester, and other thermoplastics such as asphalt bitumen.

Microencapsulation was further investigated to develop a preliminary conceptual design to provide a basis for comparison of the candidate technologies. This investigation included a specific technology literature search, additional engineering analyses, and numerous contacts with vendors and researchers. The process alternatives identified and the development of a conceptual design are presented below.

SEALOSAFE, originally marketed by STABLEX Corporation, is a full-scale commercial process which reportedly treats wastes with a polymer-type material. The waste materials are mixed with the polymeric agent in a slurry matrix. The slurry subsequently hardens to form a rock-like, low leachability material. Our inquiries revealed that the SEALOSAFE process is no longer marketed by STABLEX. Furthermore, a discussion with one of the process developers' revealed that the "polymer type" material is an inorganic cementitious (primarily fly ash) solidification agent. This process description more closely resembles the stabilization technology via lime-based techniques. STABLEX ceased marketing the process due to the difficulty in meeting EP Toxicity requirements with widely varying waste characteristics. The process was sensitive to the presence of organic compounds which inhibited proper curing. In addition, high pH must be maintained during treatment, and, subsequently, in the disposal environment in order to ensure product stability and low leachability. Since this process is similar to commercial inorganic stabilization, it was not considered to be a candidate for conceptual design.

Another process identified uses an organic polymer-modified gypsum cement called Envirostone Cement, manufactured by U.S. Gypsum Company. This process is thought to be a hybrid combination of cement stabilization and microencapsulation, using both inorganic cement and organic binders. Discussions with the vendor' indicated that the product is gypsum-based with polymer added only as an emulsifier. U.S. Gypsum has marketed the product since 1982, hoping it would lead to further growth into the hazardous waste treatment area. The company was never involved in process applications, however, and decided not to pursue further development or marketing of the process. Due to concern over meeting EP Toxicity performance criteria, it has primarily been used for waste



solidification rather than delisting or detoxification. As a result, the vendor discouraged the use of the product for this application. Since the active product component is inorganic, this process also more closely resembles stabilization technology using lime-based techniques. As a result, it was not selected for use in the conceptual design.

A commercial full-scale process has been identified using microencapsulation with an organic-based binder to treat solid and liquid wastes. This process, known as the Volume Reduction and Solidification (VRSTM) system, was originally developed to treat low-level radioactive waste streams. VRS has reportedly been applied to over 50 different types of hazardous waste streams, such as electroplating and paint sludges, and dewatered resins.

The VRSTM system has been commercialized since the mid-1960's and is currently marketed by WasteChem Corporation of Paramus, New Jersey. More than 25 systems are currently operating worldwide with over 75 unit years of operation. Numerous references describing the process and its applications are available in the literature.

The VRSTM process is a physical (nonchemical) binding process which requires intimate mixing of the feed material with the hot fluid thermoplastic. The heart of the process is a twin-screw extruder which simultaneously evaporates water from the feed stream while intimately mixing the dried feed material with bitumen (asphalt). The mixture then cools and hardens to form an asphalt block type material.

The process could utilize a wide variety of binders but the vendor (WasteChem) selected asphalt as the preferred binder due to its broad range of attractive properties, including resistance to leaching and biological attack, low cost relative to other thermoplastics, and wide availability. Tests performed by electric utilities, laboratories, and consulting firms have shown that asphalt is approximately 100 times more leach-resistant than other common solidification agents. Also, asphalt will solidify regardless of the pH of the soil or waste feed. EP Toxicity tests have shown that the microencapsulation product from electroplating and paint sludges is a nonhazardous material. The process has not been commercially applied to metals in soils, but the developers are confident that it can be successful in this application. Minimal development work is anticipated, given there are similar commercial applications with radionuclides and extensive pilot study experience.



Following processing, the hot asphalt/soil product can be cooled in molds or containers or directly disposed of in a remote area while still hot and allowed to cool in the disposal/backfill area. Upon cooling, the mixture hardens and the volume of the mix is reduced. This is due to the removal of excess water (or other solvents) from the waste. The volume reduction can be substantial when working with slurries and sludges, but is not expected to be significant with soils following the addition of asphalt at a 1:1 ratio with soil. Dry wastes treated with the VRS system are also reduced in volume due to particle size reduction, elimination of void spaces, and homogenization.

The asphalt product is not adversely affected by organics in the feed. Volatile organics may be driven off in the initial drying step, but up to 5 percent by weight of organics can be added to the asphalt blend for reincorporation into the final product.

Brenner and Rugg⁹ investigated the effectiveness of using asphalt/sulfur blends to encapsulate metals in place of asphalt alone. Personal communications with Rugg and Waste Chem Inc.^{10,11} revealed that these studies were about to enter the pilot plant-stage when funding was discontinued by the U.S. EPA in 1982. Rugg and Brenner claim that adding sulfur improves the physical and chemical properties of the product matrix. Preliminary investigations indicated that sulfur could possibly be used in quantities up to 60 percent to replace asphalt in the soil/binder blend. In terms of cost, the sulfur/asphalt blend would be advantageous due to the comparatively lower cost of the sulfur. Currently, bulk asphalt costs range from \$.08 to \$.20 per pound and bulk crude sulfur costs are on the average \$.06 to \$.07 per pound. Therefore, in comparison to a pure asphalt binder at \$.08 to \$.20 per pound, a 60-percent sulfur/40-percent asphalt binder (assuming this high sulfur ratio could be used) would improve the raw material cost to approximately \$.07 to \$.12 per pound. However, substantial bench scale and pilot plant work would be required for this application since there is currently little published data and pilot testing has not been conducted.

Other materials, such as polyethylene, polybutadiene, and polyester, have been considered and tested as organic binder materials for the microencapsulation process. However, the high cost of these materials, in comparison with asphalt, make them prohibitive. Mahalingam at Washington State University^{12,13,14} has done laboratory- and pilot-scale research on microencapsulation using polyester as the binder material. The claims for the process include applicability in a wide range of pH and "zero" leachability. The process is not commercialized as of this date due to the high cost of the polymer.



Urea formaldehyde has been used by companies, i.e., Chem-Nuclear Systems, Inc. and United Nuclear Industries, in the same context as cement for solidification of radioactive-waste streams. Raw material costs are higher than for asphalt, however, with little significant improvement in performance. Mahalingam indicated that he has consulted with users of existing cement or urea formaldehyde stabilization/solidification processes and has found that they would be prepared to convert to the polyester system, if the regulations required a "zero"/nondetectable leachability.

These studies by Mahalingam utilized soil-to-polyester ratios in the range of 50:50 to 65:35 ratio, with 50:50 being the same ratio as that used in the asphalt microencapsulation process. A comparison shows that since polyester currently costs approximately \$0.80 to \$0.90 per pound and asphalt currently costs \$0.08 to \$0.20 per pound, asphalt would provide lower cost treatment, even if the polyester could be used at the 65/35 ratio. Since the performance of the asphalt-based system is likely to exceed treatment objectives, the added cost for the use of polyester is not warranted at this time.

Following the additional information gathering and vendor contact activities described above, the VRS process, using asphalt as the binder, was selected as the basis for a conceptual design for microencapsulation. This selection is based on the attractive properties of the asphalt (i.e., ready availability, solidification under a wide range of conditions, minimal leachability, and relatively low cost), and the greater development of the process (25 operating systems), compared to the other microencapsulation technologies. The use of other, less expensive, binders, such as the asphalt/sulfur blend, could be investigated in the development program.

5.2.2 Conceptual design. The conceptual design for the microencapsulation treatment process is based on the VRS process using asphalt bitumen as the binding agent. The central process equipment is a twin-screw compounding extruder for mixing the contaminated soils with asphalt. The close tolerances of the twin-screw extruder requires that the process design include upstream processing for soil screening, and/or particle size reduction. The twin-screw extruder provides both intimate mixing of the soil and binder, and further particle size reduction of the maximum feed size of 1/4-inch to as low as 20 microns.



The soil pretreatment step could remove all oversized particles greater than 1/4-inch or, alternatively, crush all oversized particles so they could be processed. Since rock crushing becomes more difficult and expensive with larger-sized rocks, and large rocks are relatively free of contamination due to low surface area, an intermediate approach was taken which provides relatively inexpensive pretreatment. Oversize particles over 2-inches in diameter, like stones or sticks, would be screened at the excavation area, using a device such as an aggressive trommel or vibrating screen. This process should yield oversize materials free of significant amounts of adhered soil.

The quantity of these oversize particles will vary from site to site. Disposal options include direct backfilling in the excavated area, mixing with the bulk output asphalt/soil product or off-site disposal in a landfill.

Stones under 2 inches in diameter remain in the soil to be treated. The soil must be crushed to achieve a fragment or particle size no greater than 1/4-inch. Another option would be to periodically feed the oversized stones to the crusher in a low-rate multipass batch operation during outage periods for the drier and extruder, to allow careful monitoring of equipment and performance. (A crusher capable of routinely processing larger stone was not specified due to much higher equipment cost.)

The ability of the extruder to provide excess heat to vaporize moisture and to handle a high vapor load is limited. Soil should be fed to the extruder at a moisture content of 1 percent or less, or performance and/or throughput rate of the extruder will be reduced. Based on preliminary cost data from vendors, the cost for a HOLOFLITE® twin-screw type thermal processor would be comparable to those for a conventional rotary dryer.^{13,16} Since the HOLOFLITE® thermal processor (the same unit used in the Low Temperature Thermal Stripping, or LTTS, unit designed for USATHAMA) would be a component of a combined volatile organics/metals treatment process, its selection provides added flexibility. It also has the advantages of improved transportability (available as a skid-mounted unit) lower operating temperatures, and lower dust generation.

Further details of the design are presented in subsequent sections, including the design basis and discussions on major equipment.



5.2.2.1 Assumptions/conditions (basis for technology). The design parameters for the microencapsulation process are based on balancing the requirements for cost-effectiveness, i.e., a stable binder/soil product which has low leachability characteristics with the relatively low operating cost. As previously discussed, asphalt was chosen as the binder for this application, based on its favorable characteristics such as ability to solidify under a wide range of conditions, minimal leachability, ready availability, and relatively low cost. Therefore, a majority of the assumptions and process conditions are based on the requirements of the VRS/asphalt process and information from the vendor and related papers.^{3,6,7,11} The assumed operating conditions for the concept design of the microencapsulation process are as follows:

- (a) Asphalt would be used as the binder material in a 50:50 ratio by weight mixture with dry soil.
- (b) A twin screw extruder would be used to mix the asphalt and soil at the maximum process temperature of 350°F. The extruder would also serve to reduce an approximately 1/4" feed to a particle size of 20 microns for the encapsulation. In this application it is also capable of removing the residual soil moisture, up to 1 percent by weight, by evaporation.
- (c) Feed temperatures are assumed to be 70°F for the soil from the stockpile and 250°F for the molten asphalt from storage.
- (d) Electricity would be used as a heat source in the extruder.
- (e) Excavated soil composition is assumed to be:
 - 50-percent sand.
 - 30-percent clay.
 - 20-percent moisture.
- (f) For the purposes of this evaluation it is assumed that oversized material would be processed by an aggressive trommel which would separate oversized material larger than 2 inches so that it would be sufficiently free of soil/contaminants to allow for backfilling directly in the excavated area. The screened soil would be crushed to a size of 1/4 inch or less.
- (g) The soil would be dried to a moisture content of no more than 1 percent by weight, using a screw-type thermal processor, before it is fed into the extruder. A HOLOFLITE® twin screw-type thermal processor (the same unit used in the Low Temperature Thermal Stripping or LTTS, unit designed for USATHAMA) will be used, based on its competitive cost and the added flexibility of providing combined organics/metals treatment capabilities.



- (h) After drying, the soil would be screened to a particle size of 1/4 inch or less to meet the extruder feed requirements. At this point, particles larger than 1/4 inches (assumed to be 5 percent of total soil feed rate) would be fed to a crusher. The crusher output meeting the 1/4 inch criteria would be processed through the extruder.
- (i) The product would consist of the input soil and asphalt, less the soil moisture. Most of the moisture would be driven off into the vapor phase in the dryer and any residual moisture would be driven off in the extruder.

5.2.2.2 Process flow sheets. Process flow sheets were developed for microencapsulation using the design bases presented in Subsection 5.2.2.1 and Subsection 5.1. The primary focus of this study has been technologies for treatment of metals-contaminated soils. However, soils exist at several Army sites, which are contaminated with both metals and volatile organic compounds (VOC's). Therefore, at this point in the study, some consideration was given to the feasibility/adaptability of the process for treatment of soils with both metals and VOC's contamination. There are several options for treating such soils and the choice of the most feasible option is highly dependant on specific site conditions. Process optimization of this nature is not included in the scope of this study and will have to be performed during the research and development and final design stages. For this concept design, it was assumed that the VOC's would be stripped from the soil in the upstream HOLOFLITE® processor drying step. This would be done by using an adaptation of the Low Temperature Thermal Stripping (LTTS) process which has been developed for USATHAMA. This option was chosen because the process is well developed and equipment information and detailed cost estimates are readily available.

Similarly, some sites may include soils contaminated with both metals and explosives. In this case, the microencapsulation process could be combined with the soil incineration process (developed by WESTON for USATHAMA) for treatment of explosives contaminated soils. This process uses a rotary kiln incinerator to treat the explosives. The product (ash) from the incineration unit would then be fed to the microencapsulation process, which would be a modified process from the one discussed in this report. Modifications would include the elimination of the drying step. However, these modifications were not examined in detail as it would be beyond the scope of this study.



The major components of the microencapsulation process are shown in Figures 21 through 24. Figure 21 presents a block flow diagram for treating soils containing metals only. Figure 22 is the corresponding process flow diagram showing major equipment and processing steps. For information purposes, Figures 23 and 24 present the block flow diagram and corresponding process flow diagram with major equipment, respectively, for treatment of soils contaminated with both VOC's and metals. In comparison overall, the processes for treating soils with metals only and metals and VOC's are similar, due to the upstream drying requirement of the process. The basic difference is that, because the HOLOFLITE® thermal processor is used to remove volatile organics, the vapor stream must be treated. The LTS process utilizes a fume incinerator (or afterburner) to destroy the VOC's. Since heat is necessary for both the HOLOFLITE® dryer/stripper and to heat the asphalt storage tank, Figure 24 shows the vapor stream being used as combustion air for the steam boiler. Since detailed design heat and mass balances could not be performed, this should be considered a preliminary design concept for treating VOC's and metals. Without VOC's, this stream will contain only water vapor in air and should be suitable for venting to the atmosphere.

The asphalt microencapsulation process can accept up to approximately five percent of added volatile organics with only a slight softening of the asphalt product. Therefore, any organics that will not volatilize at or below the extruder process temperature may be incorporated in the asphalt/soil product (up to 5 percent).

5.2.2.3 Material balances. Preliminary material balances were calculated for microencapsulation of soils contaminated with metals only for two design base cases representing two quantities of soil to be treated (i.e., 10,000 tons per year and 100,000 tons per year). The material balances were used for determining preliminary equipment sizing and cost estimates. The following assumptions were used when developing the material balances:

- (a) The extruder and the dryer were assumed to be available for operation 325 days/year, 24 hours/day. This assumption was used to calculate the soil feed rates, other process rates, and product rates for both the 10,000 and 100,000 tons per year cases.
- (b) The material balances around the dryer and the extruder assumed no dry basis material losses in the process.

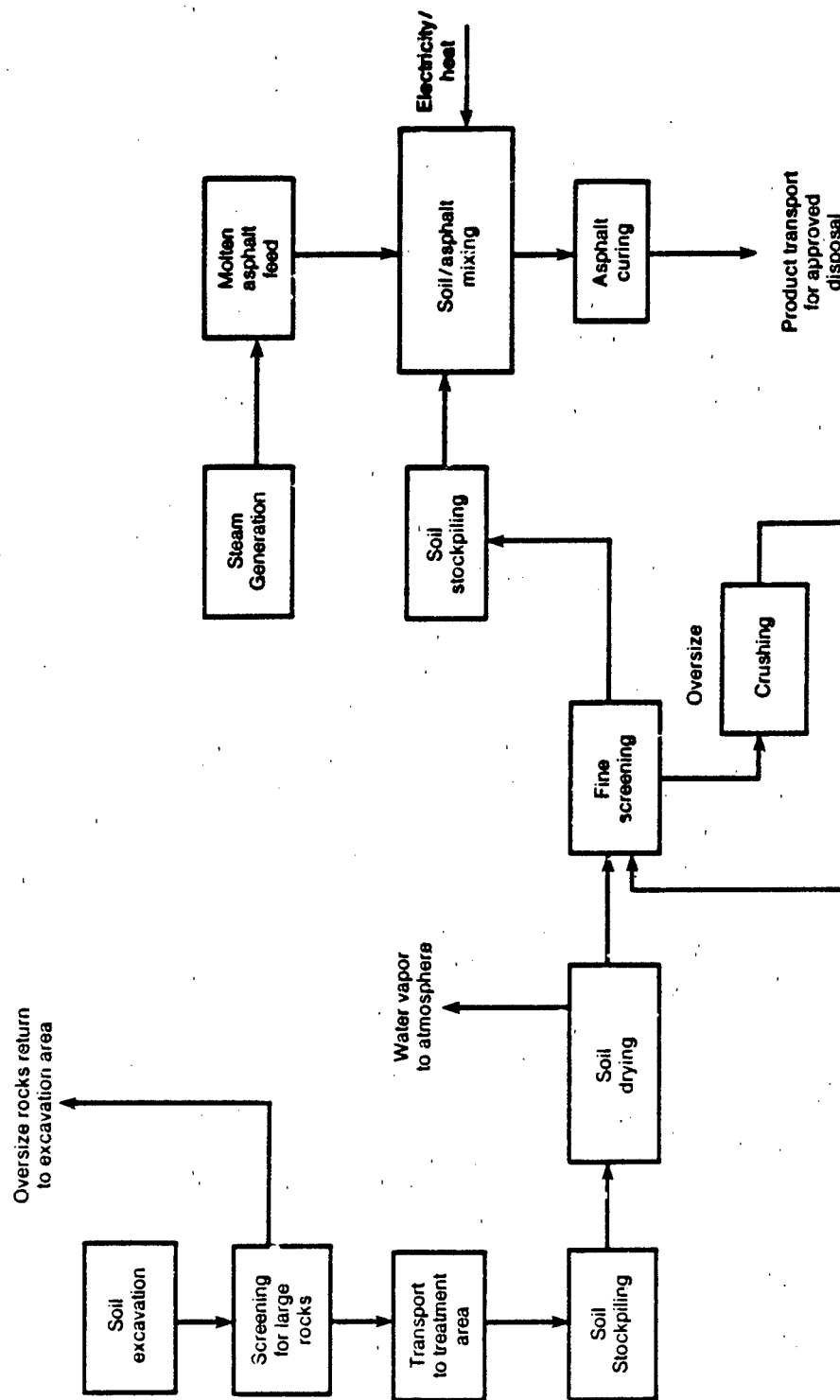


FIGURE 21. Block process flow diagram for microencapsulation of soils with metal contaminants only.

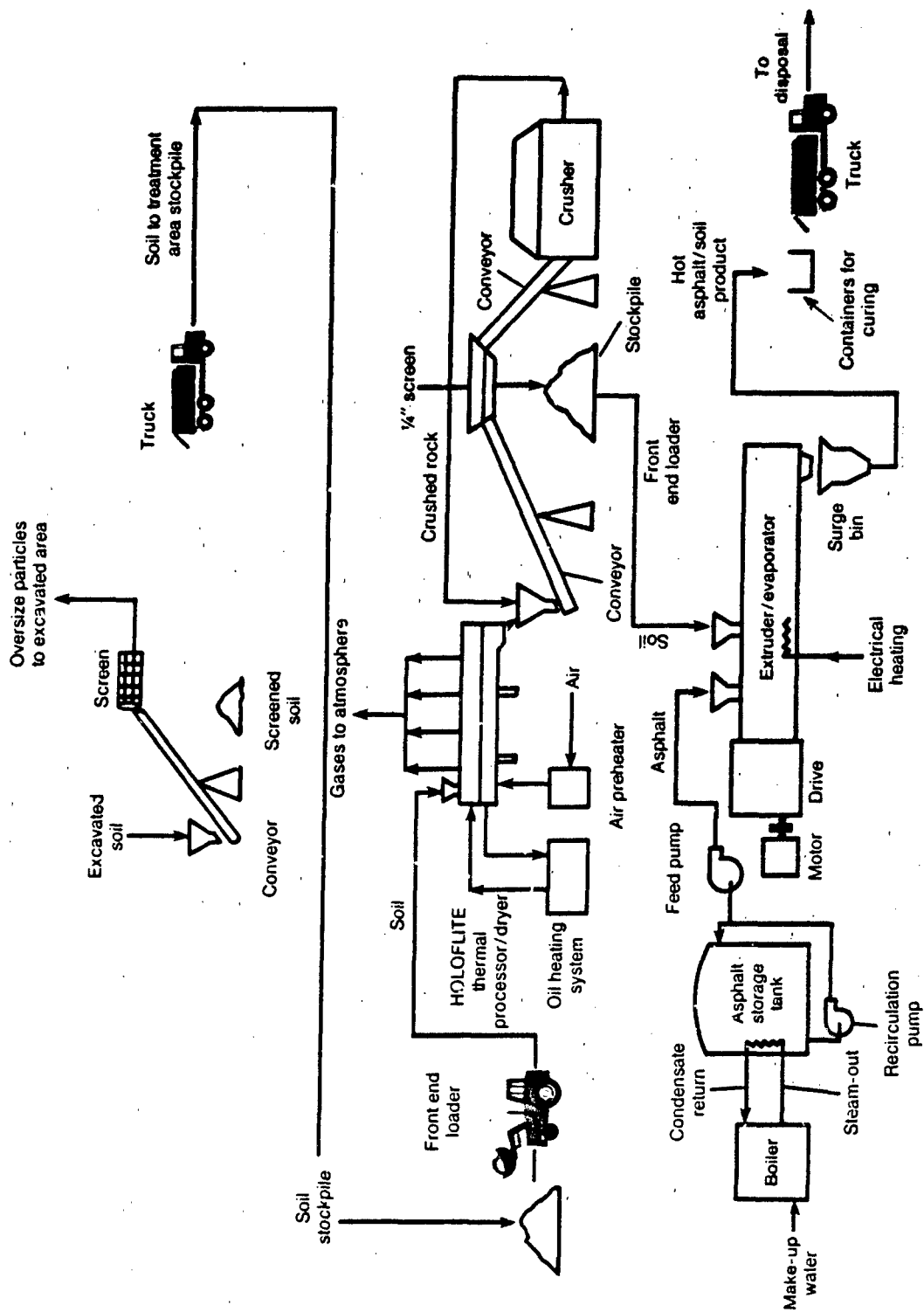


FIGURE 2.2. Flow diagram with major equipment for Microencapsulation of soils with metal contaminants only.

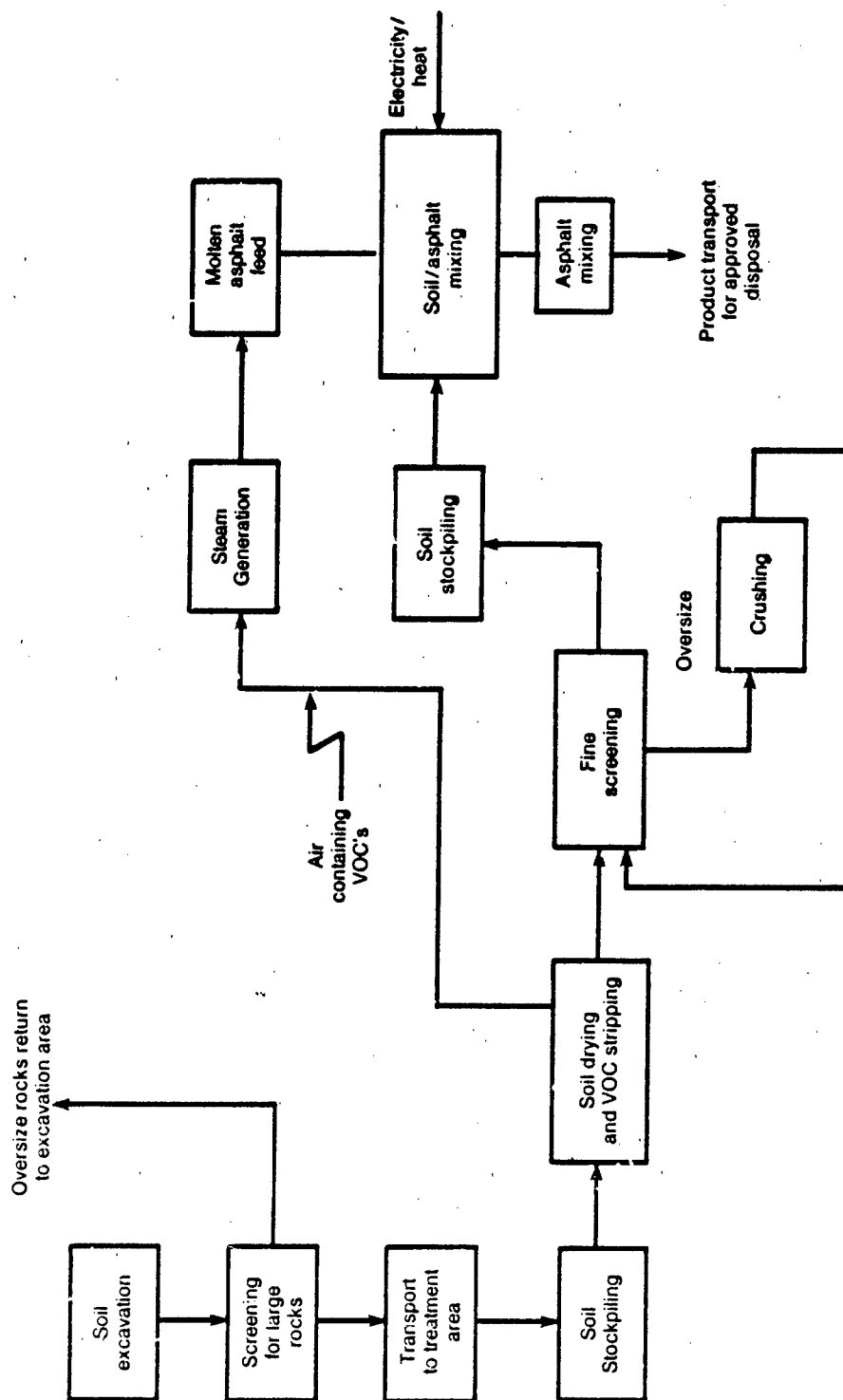


FIGURE 23. Block process flow diagram for microencapsulation of soils with VOC and metal contaminants.

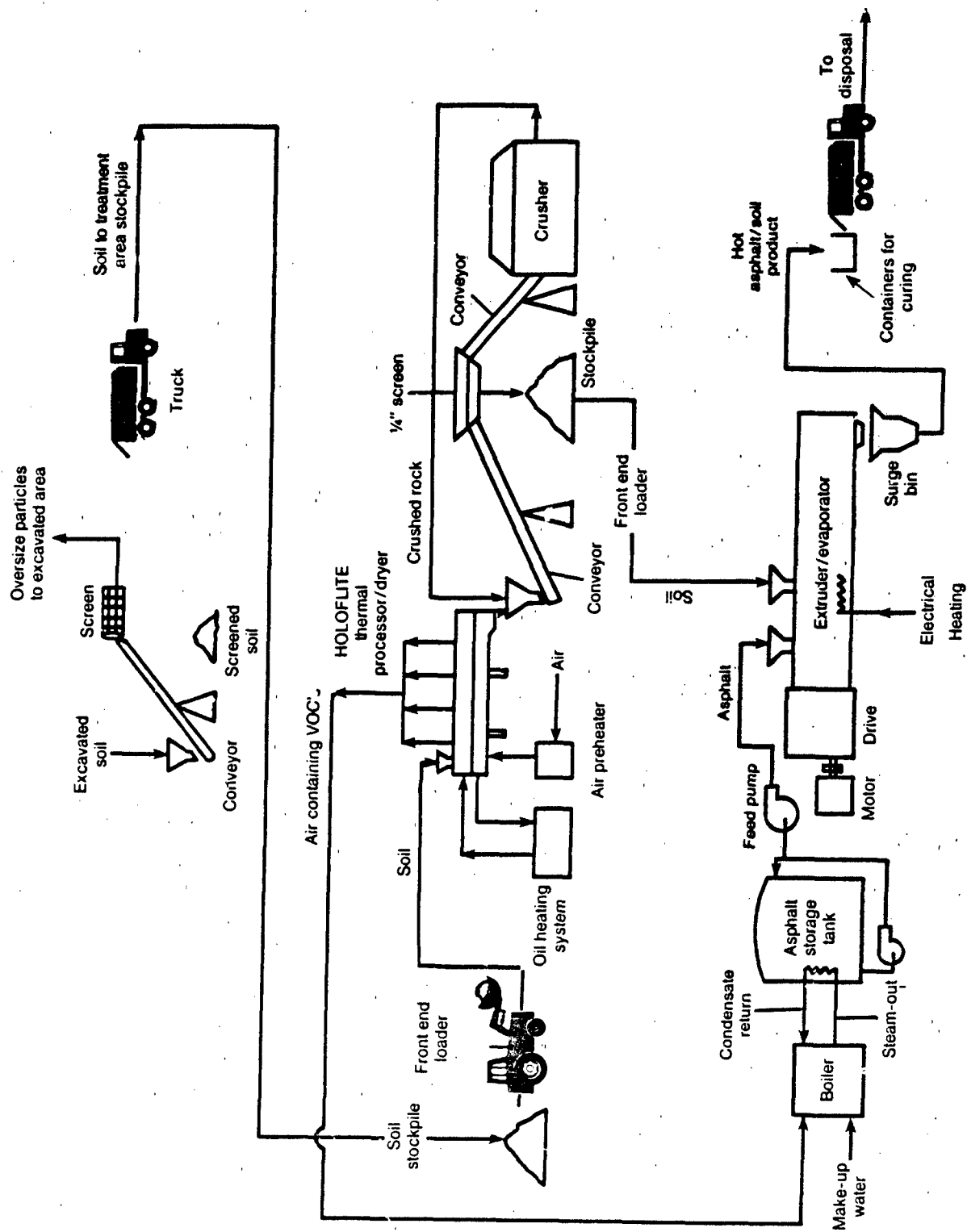


FIGURE 24. Flow diagram with major equipment for microencapsulation of soils with VOC and metal contaminants.

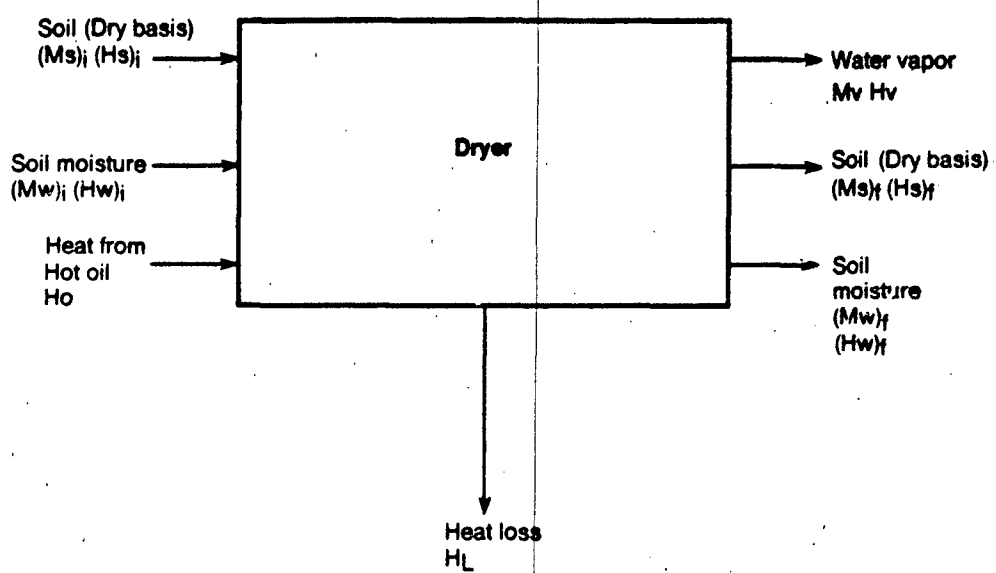
- (c) The heat balances around the dryer and the extruder were initially performed assuming no wall heat losses to yield the required theoretical heat input. The balances were then adjusted assuming a 20 percent heat loss to the surroundings for both the dryer and the extruder.
- (d) Physical properties (i.e., specific heats, specific enthalpies, etc.) for the soil, asphalt, and other process streams were obtained from standard references.^{17, 18}
- (e) The heat and mass balances were based on the assumption of an average soil composition of 50 percent sand, 30 percent clay, and 20 percent water.
- (f) The soil and water vapor were assumed to leave the dryer at 212°F, with soil moisture to be reduced from 20 to 1 percent by weight.
- (g) The soil would then cool to ambient temperature (70°F) in the subsequent screening and soil stockpiling steps.
- (h) The residual (1 percent) moisture would be evaporated in the extruder and the soil/asphalt product would leave the extruder at the process temperature of 300°F.

The heat and mass balance around the dryer is depicted in Figure 25. The heat balance equation is as follows:

Enthalpy of Soil (dry basis at 70°F)	Enthalpy of Soil Moisture at 70°F	Heat Duty of Hot Oil	Enthalpy of Soil (dry basis) 212°F
$(H_s)_i$	$(H_w)_i$	H_o	$(H_s)_f$
Enthalpy of Water Vapor 212°F	Enthalpy of Soil Moisture 212°F	Heat Loss	
H_v	$(H_w)_f$	H_L	

The results of the heat and mass balances for the dryer are summarized in Figure 26 for both soil throughput cases.

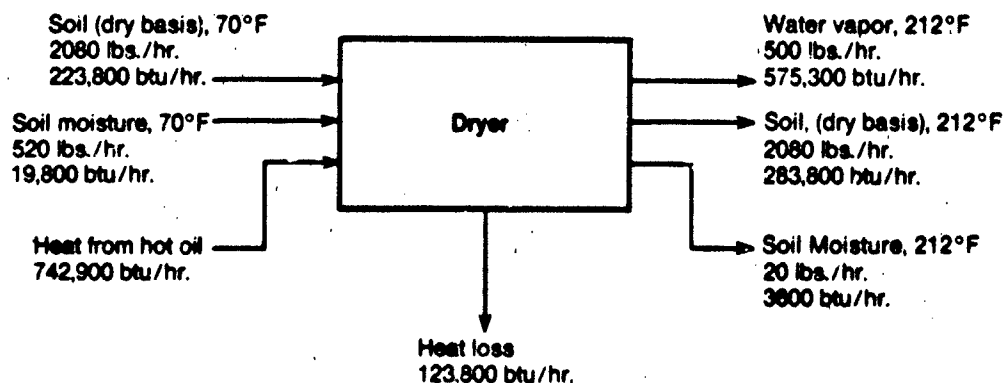
The heat and mass balance around the extruder is shown in Figure 27. The heat balance equation for the extruder is as follows:



Note:
M = Mass
H = Enthalpy

FIGURE 25 Heat and mass balance for the dryer.

CASE 1: 10,000 TONS/YEAR SOIL



CASE 2: 100,000 TONS/YEAR SOIL

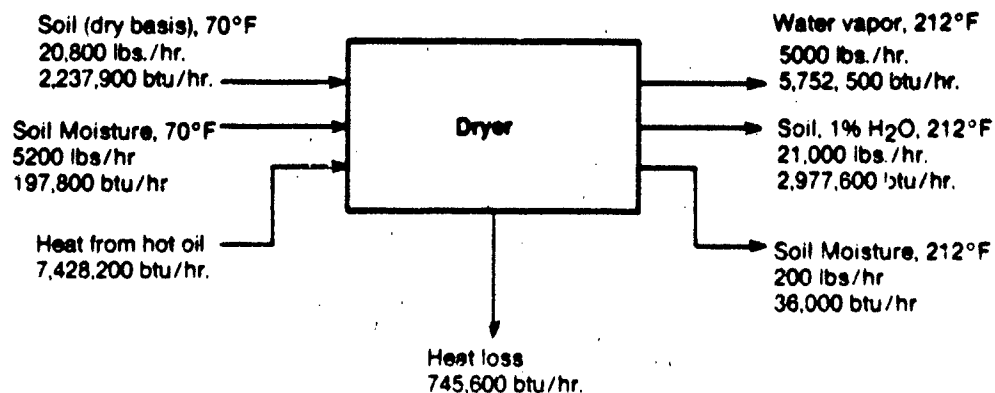
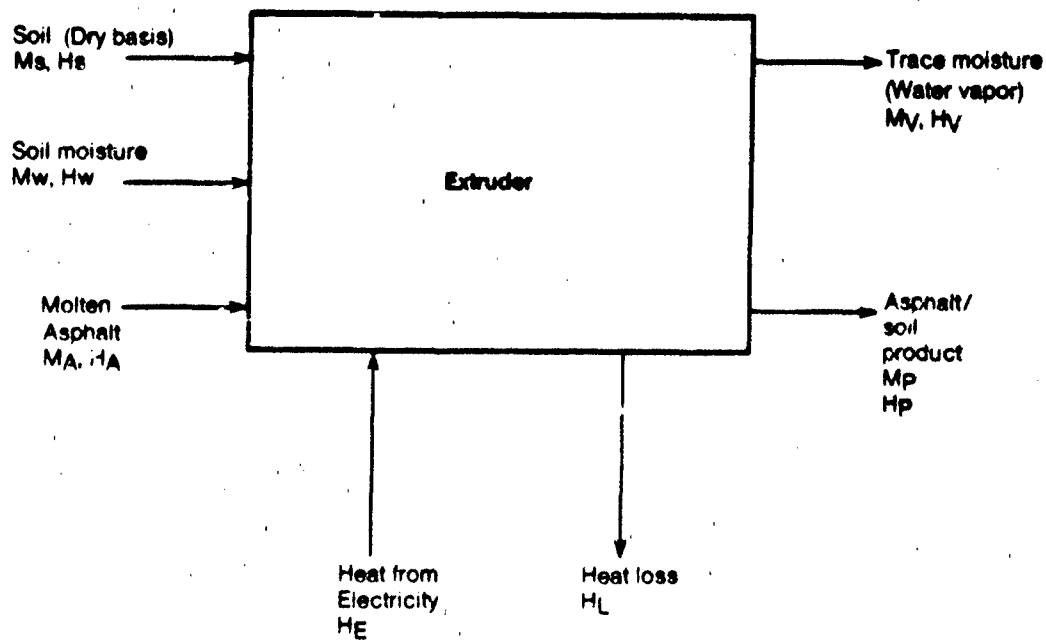


Figure 26. Summary of heat and mass balances around the dryer.



Note:
M = Mass
H = Enthalpy

FIGURE 2.7. Heat and mass balance for the extruder.



Enthalpy of Soil (dry basis at 70°F)	Enthalpy of Soil Moisture at 70°F	Enthalpy of Asphalt, 250°F	Heat Duty of Electricity
(H _s)	(H _w)	(H _A)	(H _E)
	Enthalpy of Asphalt/Soil product at 350°F	Enthalpy of Trace Moisture, Water Vapor 350°F	Heat Loss
	(H _p)	(H _v)	(H _L)

The heat and mass balances for the extruder are summarized in Figure 28 for both soil throughput cases.

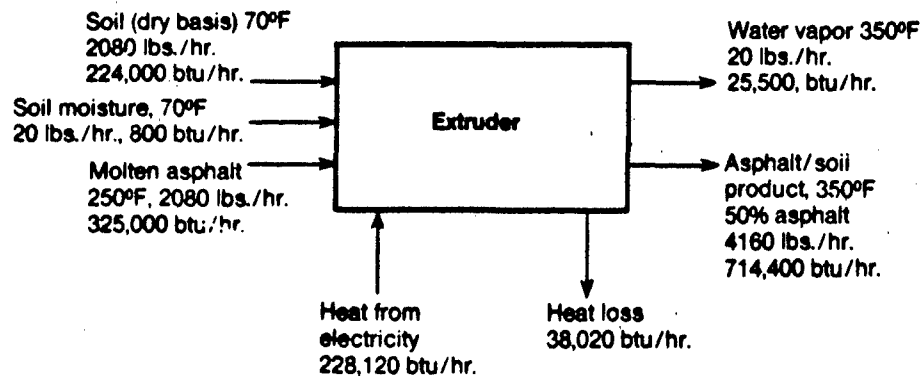
5.2.2.4 Major equipment. As discussed in Subsection 5.1, the process design and costing were generally based on a stationary on-site treatment unit. However, consideration was given to using mobile or portable equipment, where possible, to make it easier to relocate the process to another site. Most of the commercially available equipment for the microencapsulation process is, in fact, portable or readily transportable, with the exception of the asphalt storage tanks.

Both the HOLOFLITE® thermal processor and the VRS™ extruder/ evaporator are typically shop-fabricated on skids and are readily transportable. Also, the process design includes portable, self-contained material handling equipment which can be easily moved from site to site.

Other more transportable options for on-site asphalt storage could be pursued in the future, such as the use of several smaller size transportable storage tanks or, where feasible, the use of railroad tank cars for both transport and on-site storage of the asphalt.

Since equipment cost is not sensitive to size at these low soil handling capacities, it was found that the same handling equipment can be used for both soil throughput cases. Therefore, the major differences in equipment sizes for the two cases (10,000 and 100,000 tons per year) are with the dryer (HOLOFLITE® thermal processor), twin-screw extruder, asphalt storage tanks, and associated equipment.

CASE 1: 10,000 TONS/YEAR SOIL



CASE 2: 100,000 TONS/YEAR SOIL

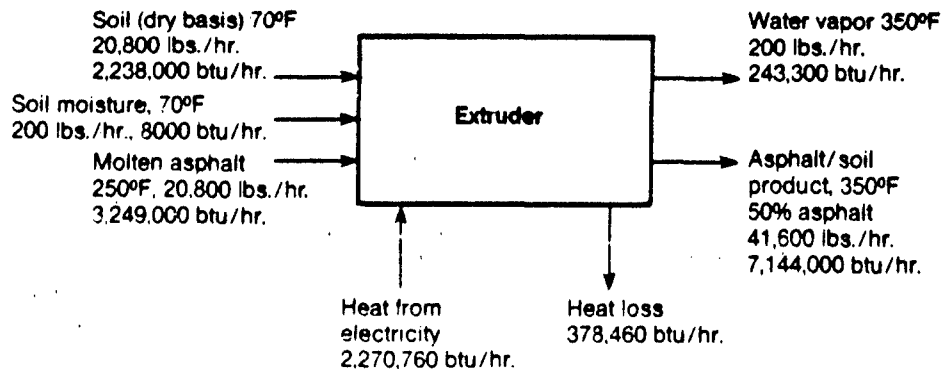


FIGURE 2.8. Summary of heat and mass balances around the extruder



The various pieces of equipment for microencapsulation were selected based on the engineering analysis and conversations with equipment vendors.^{5,11,15,19,20,21} The following is a list of major equipment for both soil quantity cases evaluated:

Number	Description	Purpose
<u>Case 1 - 10,000 TPY</u>		
1.	HOLOFLITE® Thermal Processor (dryer) Model D2424-6 with baghouse	Soil moisture reduction
2.	Hot Oil (600°F) Heater/Circulation System with 720,000 Btu/hr Theoretical Loading	Heat duty for dryer
3.	Steam Boiler, Oil Fired, 109,000 Btu/hr output	Keep asphalt molten at 250°F
4.	19 ft 6 in. x 24 ft; 50,000 gallon Carbon Steel Storage Tank with Steam Coils	Asphalt Storage
5.	Extruder/Evaporator including controls, asphalt feed, motor drive; 120 mm diameter unit	Mix asphalt/soil for encapsulation
<u>Case 2 - 100,000 TPY</u>		
6.	HOLOFLITE® Thermal Processor (dryer) Model Q24/24 with 20 hp Motor Drive with baghouse	Soil moisture reduction
7.	Hot Oil (600°F) Heater/Circulation System with 7 million Btu/hr Theoretical Loading	Heat duty for dryer
8.	Steam Boiler, Oil Fired, 1,160,000 Btu/hr output	Keep asphalt molten at 250°F
9.	3 - 100,000 gallon (27 ft x 24 ft) Carbon Steel Storage Tanks with Steam Coils	Asphalt storage
10.	Extruder/Evaporator including asphalt feed, controls, motor drive; 2-160 mm diameter units	Mix asphalt/soil for encapsulation



Number	Description	Purpose
<u>Equipment Common to Both Cases</u>		
11.	Portable conveyor 24 in. x 50 ft with feed hopper and 1-way sloped grizzly (bottom) and 2 in. open trommel (top)	Remove large rocks and debris
12.	Portable conveyor 24 ft x 50 ft with regulated feed hopper (bottom)	Feed screened soil to dryer
13.	Portable conveyor 24 ft x 50 ft with regulated feed hopper (bottom) and 1/4 in. open vibrating screen (top)	Screen out particles >1/4 in. for extruder
14.	Portable Conveyor	Feed >1/4 in. particles to crusher
15.	Vertical Shaft Impactor Gravel Crusher maximum 5 ton/hr	Crush oversized soil and rocks to 1/4 in.
16.	Curing Containers	Accept hot asphalt/soil product out of extruder and stage for curing, QC, and transport to excavation area

All of the portable materials handling equipment described above are fully self-contained and diesel-powered to facilitate remote site operation. The steam boiler is oil fired and the hot oil heater can be oil or propane gas fired. Electricity can be provided for other equipment (motors, extruder), as necessary, by portable diesel fueled generators.

As previously discussed, soils which are contaminated with both organics and metals can be treated by microencapsulation using much the same equipment as described above. Although a detailed analysis of this option was not conducted, only minor process modifications are anticipated due to the compatible requirements of the LTTS and microencapsulation processes, as described earlier.



5.2.3 Cost estimates. Preliminary concept level cost estimates were developed for the design basis given in Subsection 5.1 and the process described in Subsection 5.2.2.2 for the microencapsulation system. The conceptual design is based on using the HOLOFLITE® thermal processor for drying due to the compatible requirements for LTTS treatment of VOC's and microencapsulation. Because the thermal processor (from the LTTS process) is used for drying in both cases, and it is assumed that the off-gases containing VOC's could be oxidized in process heating equipment needed in both cases, the equipment and operating costs for treatment of soils containing metals and VOC's would be approximately the same as that for soils containing metals only, for this technology.

These cost estimates include both capital and operating costs. Equipment cost estimates were obtained from vendors^{15,19,20,21} for most of the major equipment components. Other cost information was obtained from Mean's Mechanical Cost Data²² and a previous WESTON study for USATHAMA on the LTTS process ("Economic Evaluation of Alternative Options for Low Temperature Thermal Stripping of Volatile Organic Compounds from Soil") for removal of volatile organic compounds from soils.²³

Concept level costs were estimated based on major components of the microencapsulation process for comparison with the other two technologies. As indicated in Subsection 5.1, costs associated with specific process siting, such as transportation of soil to a central treatment site and long utility connections, were not calculated for all three technologies studied in this report.

Unit costs for labor, rental equipment, and utilities are presented in Subsection 5.1.3. The following unit costs were assumed for materials specific to microencapsulation:

Description	Unit Cost
Asphalt (average of current bulk rates)	.10/lb



Costs for equipment for transportation and installation at the job site were included with the equipment cost estimates. A factor of 10 percent of the equipment cost was used for equipment that is fully assembled and portable. A factor of 50 percent was used for skid-mounted equipment where it was anticipated that some field modifications and significant ancillary equipment installation and interconnection efforts may be required.

Table 11 contains a summary of the total projected costs for soil treated by microencapsulation for both cases of 10,000 and 100,000 tons of soil per year. Based on the assumptions used here, these costs are applicable to both the treatment of soils contaminated with metals only and soils contaminated with metals and organics. It should be noted that these are concept level cost estimates which are intended to be used for comparative purposes only for the three technologies addressed by this study. There is a considerable amount of applications testing and process optimization which remains to be completed.

The cost projections show that the capital costs for microencapsulation are low in comparison with the operating costs, especially for the 100,000 tons of soil per year case. It must be noted that the largest single component of the operations cost is the cost of the asphalt. The cost of asphalt represents approximately 50 to 80 percent of the projected operating cost and 35 to 70 percent of the overall treatment cost for the cases evaluated. Therefore, the overall cost of the process is very much dependent on the available price of asphalt, the soil/asphalt ratio and the potential for developing lower cost binding agents. The binding agent cost and utilization is the critical factor in the process development and optimization because the cost and amount of binder currently needed to treat a given amount of soil is considerable.

Overall, the cost summary table shows that the 100,000-ton per year of soil processing rate represents the more cost-effective case.

5.2.4. Requirements for development. The VRS process for microencapsulation of wastes is a commercially available process. Since it has not been applied to metals contaminated soils, however, some development work would be required for this particular application.



TABLE 11. ESTIMATED TOTAL PROJECT COSTS FOR
MICROENCAPSULATION OF SOILS CONTAMINATED WITH METALS
ONLY OR VOC's AND METALS

Item	Case 1	Case 2
	10,000 TPY (Dollars)	100,000 TPY (Dollars)
<u>Capital (Includes</u> <u>Transportation and Installation</u>		
HOLOFLITE® Processor (for Drying and Stripping VOC's)	669,000	1,630,000
VRS Extruder (for Mixing Soil and Asphalt)	488,000	1,200,000
Soil Screening, Conveying, Handling and Other Ancillary Equipment	<u>343,000</u>	<u>670,000</u>
Subtotal	1,500,000	3,500,000
<u>Operations and Maintenance</u>		
Labor	1,450,000	1,870,000
Equipment Rental	400,000	685,000
Raw Materials and Major Utilities	<u>1,800,000</u>	<u>16,945,000</u>
Subtotal	3,650,000	19,500,000
<u>Technology Implementation</u>		
Designs, Plans, Specifications, and Regulatory Approval -20% of Capital	300,000	700,000
<u>Contingency at 25% of Summed</u> <u>Up Costs for Capital, O&M and</u> <u>Implementation</u>	<u>1,360,000</u>	<u>5,925,000</u>
Total Project Cost	6,810,000	29,625,000

Notes: Total project cost assumes single use and operation for
one year.
No salvage/reuse value has been attributed to the equip-
ment.



5.2.4.1 Data gaps. The primary data gaps that should be addressed for microencapsulation include:

- (a) Identify more cost-effective binders and/or diluents.
- (b) Evaluate the ratio of asphalt to dry soil. A ratio of 50:50 has been used in this evaluation and was most often found to be necessary in the published studies. In some cases, the ratio has increased up to 70-percent dry waste to 30-percent asphalt. It would be valuable to maximize this ratio while still keeping the leachability qualities of the product so as to reduce the asphalt costs.
- (c) Verify recommended process temperatures and determine grade of asphalt needed.
- (d) Confirm TCLP and EP Toxicity data on asphalt/soil product.
- (e) Determine the effect of soil type, including percent oversize materials (rocks), particle size distribution, and clay, silt, sand, and moisture content.
- (f) Compile pilot and full-scale operational data including feed and product rates, cycle times, recycle rates, down times, product handling requirements, detailed heat and mass balances, temperature profiles, process temperatures, etc.

5.2.4.2 Development program outline. If microencapsulation were chosen as the technology for further study and possible future implementation, then a development program would be required to fill the significant data gaps. The following is a preliminary outline for such a developmental program:

- (a) Laboratory program to:
 - Investigate potentially more cost-effective binders and/or diluents.
 - Establish the minimum grade of asphalt needed by varying the grade of asphalt for a constant temperature and asphalt to dry soil ratio.
 - Establish optimum asphalt to dry soil ratio by varying the ratio for a constant process temperature, soil, moisture content, etc.
 - Establish process temperature by varying the temperature for a constant asphalt/soil blend.
 - Determine the effect of soil type by testing 2 to 3 divergent soil types.
 - Analyze asphalt/soil products by TCLP and EP Toxicity tests to confirm non-hazardous characteristics and encapsulation effectiveness.
 - Perform a weathering test to determine freeze/thaw effects.



(b) Pilot scale test program to establish:

- Operating parameters such as dryer retention time/product feed, exit temperature, binder ratio, extruder speed, process temperature, etc.
- Detailed heat and mass balances.
- Utility and fuel requirements.
- Product quality (TCLP and EP Toxicity tests).
- Revise cost estimates for full-scale system.

5.2.4.3 Estimated development costs. Estimates for development program costs should be made based on a more detailed development test plan. Even costs estimated on that basis are subject to change due to questions and data needs which arise during the development program. Order of magnitude development program costs were developed only for the purposes of comparison between technologies.

Even though the VRSTM process is commercialized, it has not been applied to soils/metals, and a small laboratory bench-scale program would be required to verify the operating conditions and the quality of the product in addition to investigating more cost-effective binding agents. Such a program could range in cost from \$50,000 to \$100,000. Costs for the other phases of the developmental program cannot be estimated at this time because they would be based on the outcome of the laboratory program.

5.2.5 References

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5.3 Roasting

5.3.1 Discussion. In the roasting process, the heavy metals in the feed material are immobilized in a vitrified inorganic matrix. As the contaminated soil material is heated it passes through the following stages:

- (a) Evaporation of the residual water.
- (b) Decomposition of hydroxides and salts to form the corresponding oxides.
- (c) Sintering, the fusing together of solid particles without reaching the liquid state, occurs at about two-thirds of the melting temperatures (absolute-°K).
- (d) Melting of heavy metal oxides (around 2,000°C).

The roasting process heats the feed material to between sintering and melting temperatures where heavy metals are immobilized in the semi-solid slag. X-ray diffraction photographs of the sintered slag show that the metals are in the dispersed phase while the silica melts to form the continuous phase. Organic waste components would be destroyed by combustion at the operating temperatures of 2,000°F in the roaster. Since immobilization is the objective of this process, volatilization of metals should be minimized. To achieve this, silicates in the form of clay minerals (i.e., kaolinite), sodium hydroxide, and ferric oxide may be added to the melt if not present in the waste or soils. These additives yield a more viscous melt and raise the boiling point of the metal compounds

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in the melt. Roasting of contaminated soils has not been studied, but naturally occurring silica in soil may provide the same benefit as the silicate additives (i.e., having the viscosity of the melt and boiling point of the metals) for soil treatment.

Some related work on treatment of liquid radioactive wastes by vitrification has been conducted in the United States and Europe. The most pertinent vitrification method is the French AVM process. This technology utilizes a two-stage vitrification process. The first stage consists of a rotary kiln where the liquid radioactive waste is calcined. The calcined solid radioactive waste is mixed with "glass formers" and subsequently vitrified (fully melted and glassified) at high temperatures in an electrical furnace. The product, a molten glass, is poured into canisters, cooled, and transferred to a disposal facility.

In another project, researchers at the U.S. Department of the Interior's Bureau of Mines conducted a pilot scale test on the calcination of kaolin using a rotary kiln. The intent of this test was to determine if alumina (Al_2O_3) could be extracted from calcined kaolin. Their experiments showed that kaolin processed at 750 - 775°C yielded a product from which alumina could be easily extracted using HCl. They have also shown that kaolin processed at temperatures >1,000°C results in spinel formation which prevents the extraction of alumina from the product. This phenomenon is similar to the mechanism of metal immobilization in roasting slag, predicted by Kox and Van Der Vlist.

Since the technology involves immobilization of the metals in a nearly molten or molten stage, a roasting furnace which can handle this slag would be required. The rotary kiln and the Flammenkammer oven were suggested as possible furnaces which could be used in the process. The rotary kiln is a commonly available furnace which is extensively used in the cement industry and was, therefore, selected for use as the roasting furnace in this concept design. Flammenkammer ovens are not used in the cement industry. Additives like kaolin are inexpensive and widely available in the United States.



The concept design uses a process wherein the contaminated soil would be excavated and screened to remove oversized materials and rocks. This screening was necessary to meet the equipment tolerances for subsequent processing of additives and soils through a mixer. The mixture of screened soil and the additives would then be fed to the rotary kiln to be roasted. Moisture would be driven off into the vapor phase and exit the kiln with the combustion gases. Organic compounds may be oxidized or driven off into the vapor phase depending on their volatility, combustability and retention time in the kiln. The gases from the kiln would be passed through a dust control device to control particulate emissions. The molten slag would be cooled in a grate cooler and the product subsequently reduced in size using a jaw crusher. Based on analytical data, the crushed slag could either be used to backfill the excavated area or transported for disposal.

5.3.2 Conceptual design.

5.3.2.1 Assumptions/conditions (basis for technology). Kox and Vlist¹ indicated that the leachability of metals from the slag decreases with increasing kiln operating temperature. Data show that the leachability is lowest at 1,300°C (2,500°F). They also show that the leachability decreases with increasing additive content. Based on the information contained in this paper and related work,^{2,3,4} certain assumptions were made in order to further develop the conceptual design and preliminary cost estimates. These include:

- (a) The additive would be low-grade kaolin clay added at a soil to kaolin ratio of 3:2.
- (b) The soil and kaolin mixture would be heated by combustion gases flowing in a counter-current direction in a rotary kiln.
- (c) The kiln hot end temperature (slag temperature) would be 2,500°F.
- (d) The soil feed temperature would be 70°F.
- (e) A fuel oil (No. 2) burner would be used in the kiln. It is assumed that 30 percent excess air would be required for combustion and flame propagation.
- (f) The burner combustion air inlet temperature would be 70°F.
- (g) The temperature of combustion product gases exiting the kiln would be 700°F.
- (h) The input soil composition would be:
 - 50-percent sand.
 - 30-percent clay.
 - 20-percent moisture.



- (i) Soil moisture would be driven off into the vapor phase and exits the kiln at the same temperature as the combustion gases (i.e., 700°F).
- (j) Soil and kaolin would be mixed in a pugmill mixer prior to feeding the mixture to the kiln. Although the pugmill design is forgiving with respect to large or oversized particles, rocks larger than 2 inches in diameter should be screened to assure reliable operation of the pugmill.
- (k) Oversized rocks would be screened at the excavation area, using an aggressive trommel. This screening process should yield oversize materials free of significant quantities of adhering soil.
- (l) The quantity of oversize materials will vary from site to site. For the purposes of this concept design, it was assumed that the aggressive trommel would produce oversized materials with low levels of adhered soil and could be classified as uncontaminated. Therefore, the oversize material could be backfilled on-site.
- (m) The combustion gases would be cooled and passed through a baghouse for particulate emission control. Baghouse dust would be returned to the kiln for roasting.

It must be noted that the focus of this study is on technologies for treating metal contaminated soils. However, at many Army sites, soils are contaminated with metals and volatile organic compounds (VOC's). Therefore, some consideration was given to adapting this process for treating soils contaminated with both VOC's and metals.

There are several options for treating such soils and the choice of an option would depend on the site conditions. Process optimization of an organic/inorganic contamination mixture should be performed during the R&D and final design phases.

VOC's could probably be combusted by modifications to the process, including concurrent firing and, possibly, a secondary chamber to provide longer gas residence time. However, there are disadvantages associated with these changes, such as higher energy costs due to the higher gas exit temperature. At this concept design stage, it was assumed that the VOC's would be stripped from the soil prior to roasting by using the HOLOFLITE® processor from the Low Temperature Thermal Stripping (LTTs) process which has been developed for USATHAMA. This option was chosen because it would be more energy-efficient, the process is now well developed, detailed cost estimates are available, and the equipment can also serve as a mixer of the soil and kaolin instead of the pugmill mixer.



Similarly, some Army sites may include soils contaminated with both metals and explosives. In this case, the roasting process may be combined with the soil incineration process (developed by WESTON for USATHAMA) for the treatment of explosives-contaminated soils. Since explosives incineration utilizes a rotary kiln incinerator, it could be modified to treat soils contaminated with both explosives and metals. Due to the explosive hazard, soil would first be processed through the normal explosives incineration process. The ash would then be mixed with additives and fed to a counter-current roaster to increase the final temperature to ensure that the metals are immobilized. These modifications were not examined in detail as it would be beyond the scope of this study.

5.3.2.2 Process flow sheets. Flow sheets were developed for this process based on the assumptions given in Subsection 5.3.2.1 and Subsection 5.1. Accordingly, a block flow diagram for the roasting process of treating soils contaminated with metals is presented in Figure 29. Figure 30 is the corresponding process flow diagram showing the major equipment and processing steps for roasting.

Similarly, Figures 31 and 32 are the block flow diagram and process flow diagram respectively, with major equipment for treating soils contaminated with both VOC's and metals by means of roasting. The flow sheets for treatment of soils with VOC's and metals are presented here only to show the flexibility of the process to adapt to different site requirements. In the subsequent section, material balances were performed only for the process used to treat soils contaminated with metals. The later sections on major equipment and costs also deal mainly with treatment of soils contaminated with metals only.

This approach was taken to limit the number of subalternatives evaluated at this early stage of technology development. Evaluation of subalternatives and process optimization are best conducted in the later stages of development. Approximate costs are presented, however, for the combined VOC's/metals process, using information from the Low Temperature Thermal Stripping studies previously conducted by WESTON for USATHAMA.¹²

5.3.2.3 Material balances. Material balances were developed, based on the preliminary conceptual design assumptions, to support the preliminary cost estimate. Balances are provided for treatment of soils contaminated only with metals. The following additional assumptions were used in developing the balances for the hypothetical cases evaluated (i.e., 10,000 TPY and 100,000 TPY of soil):

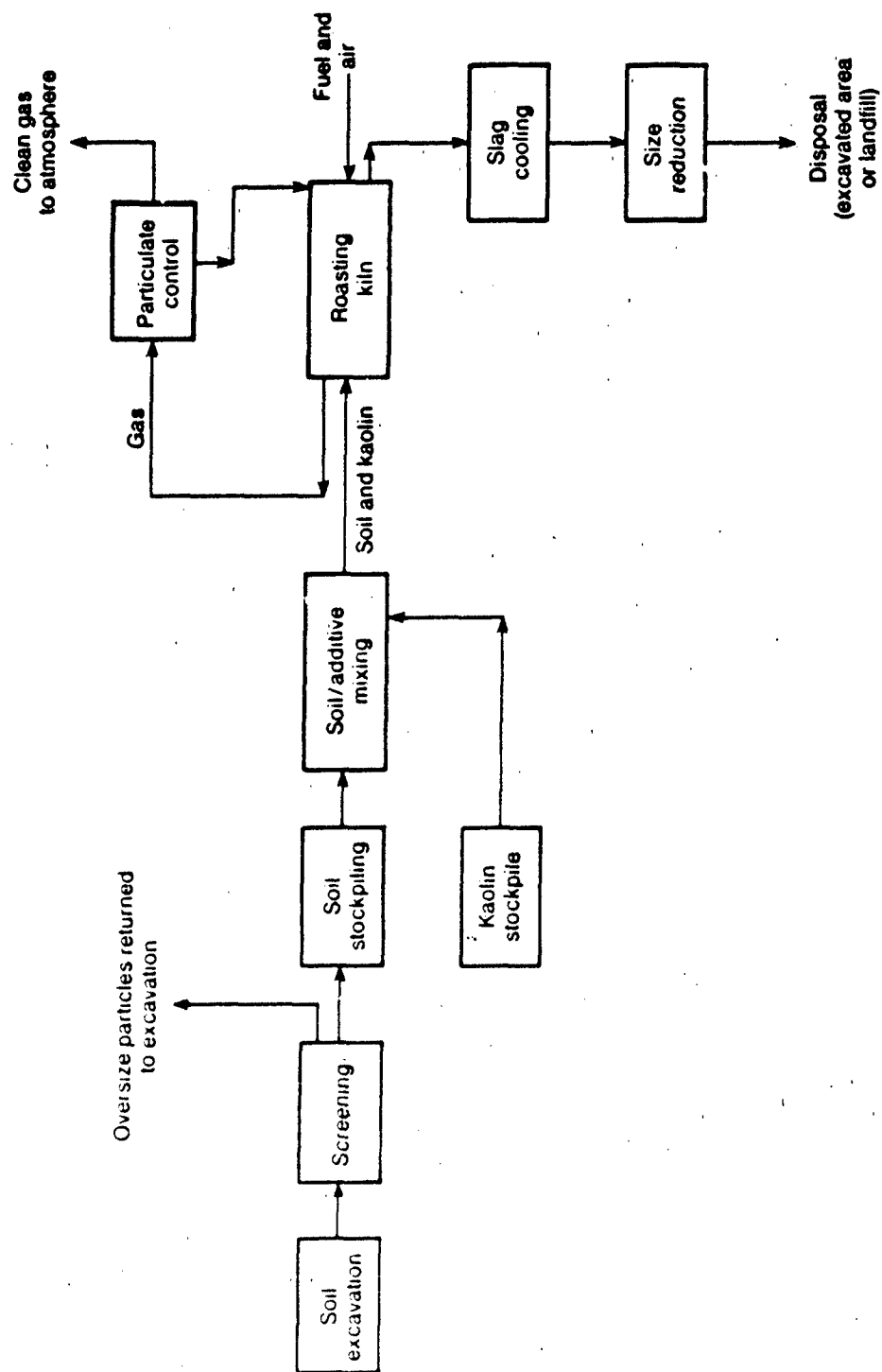


FIGURE 29. Block flow diagram for treatment of soils with metal contaminants only - by roasting.

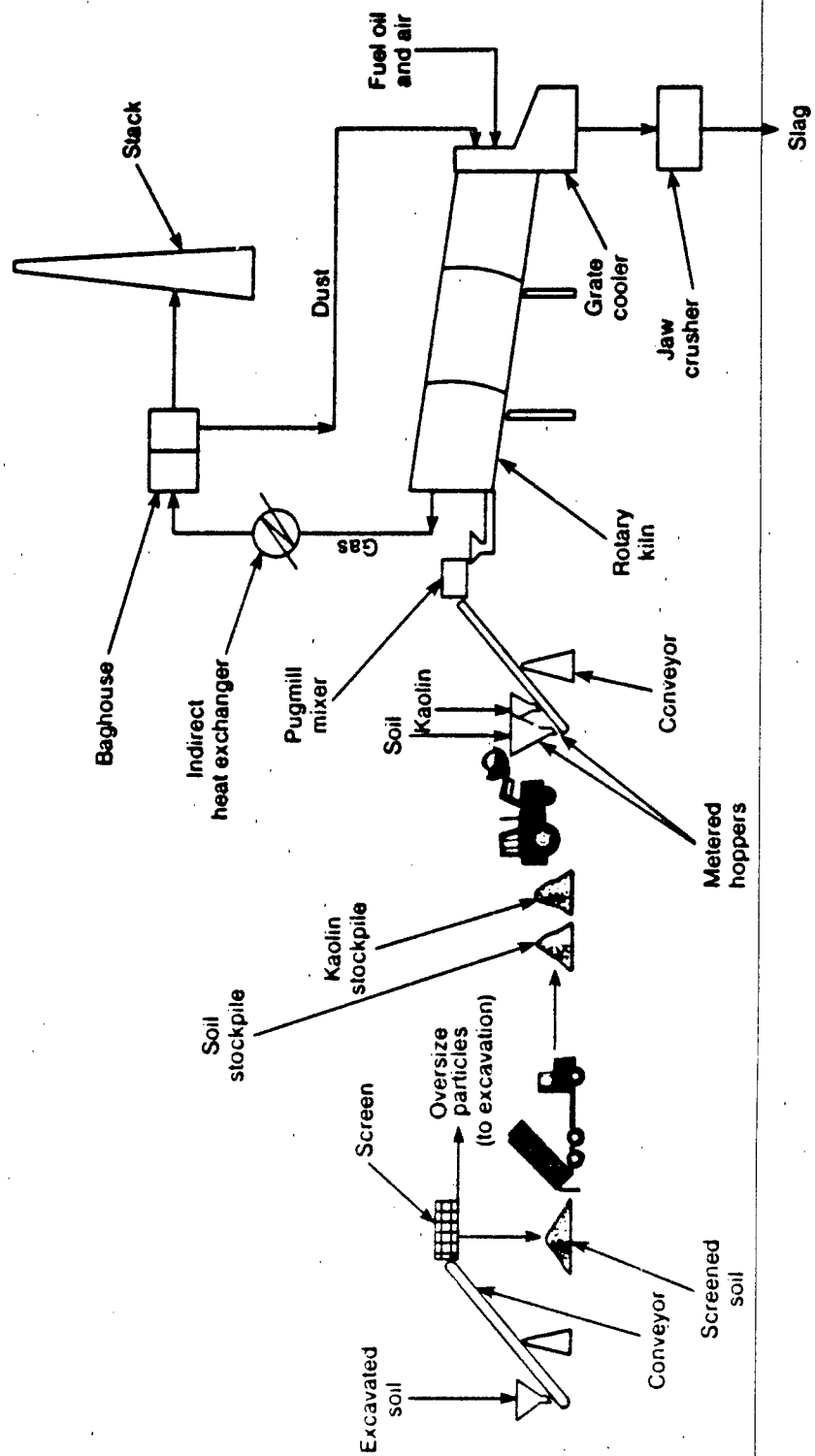


FIGURE 30. Flow diagram with major equipment for treatment of soils with metal contaminants only - by roasting.

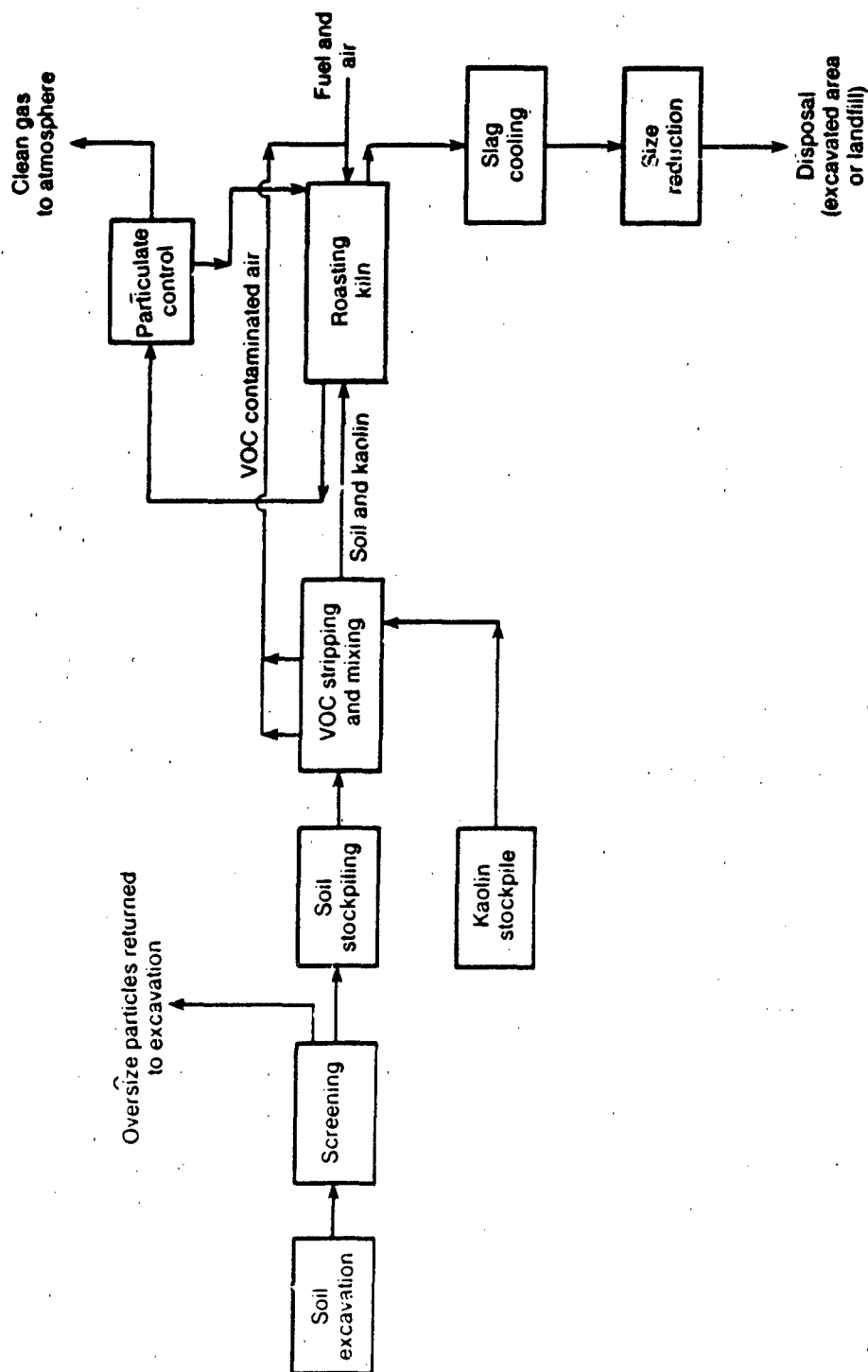


FIGURE 31. Block flow diagram for treatment of soils with VOC and metal contaminants - Low Temperature Thermal Stripping followed by roasting.

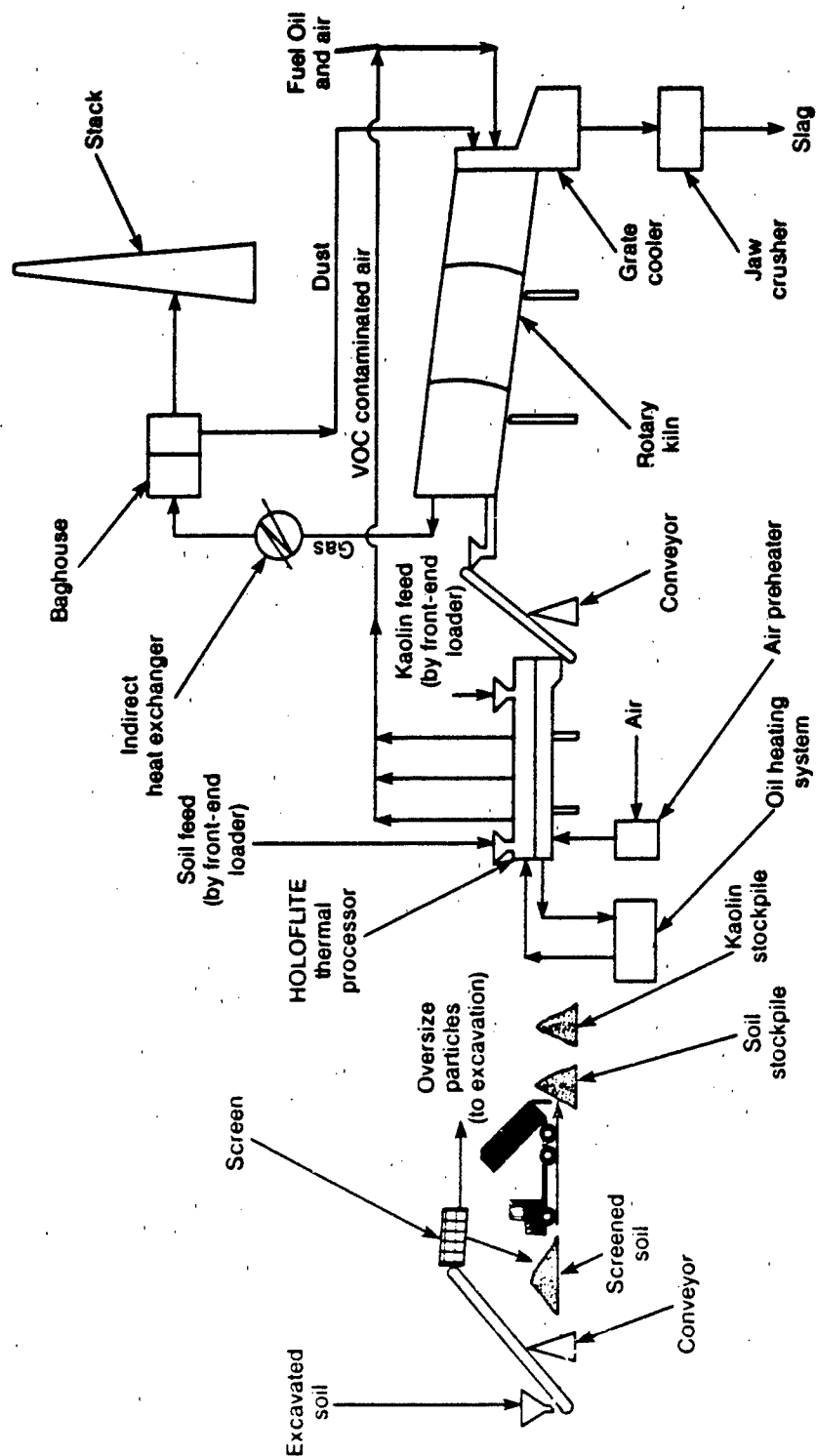


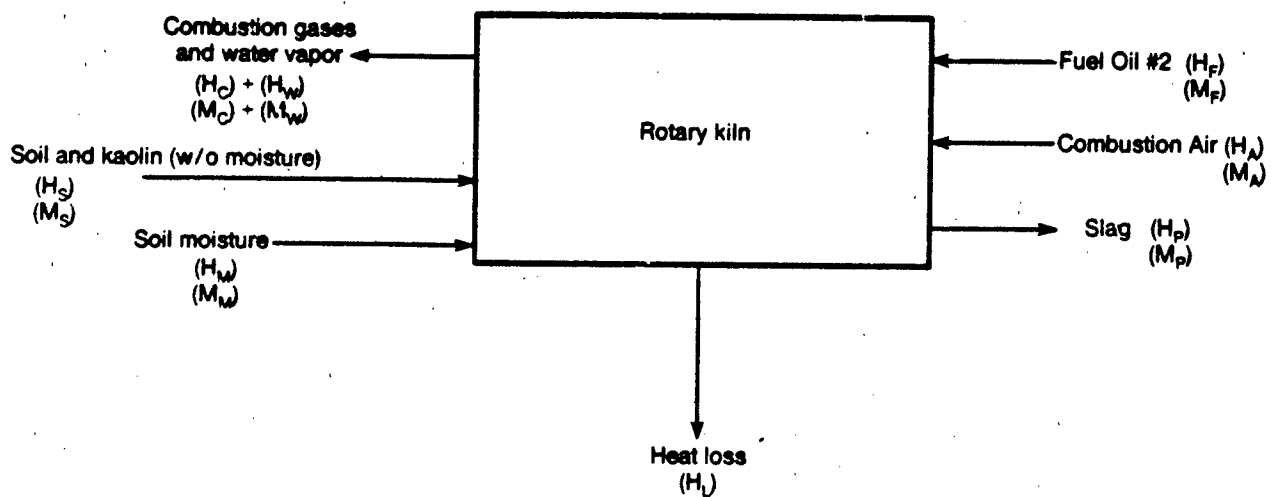
FIGURE 32. Flow diagram with major equipment for treatment of soils with VOC and metal contaminants - Low Temperature Thermal Stripping followed by roasting.



- (a) The rotary kiln was assumed to be operational 300 days a year, 24 hours a day. This was used to calculate the feed and product rates necessary for 1-year completion of treatment at sites containing 10,000 tons and 100,000 tons of contaminated soil.
- (b) Figure 33 depicts the heat and mass balance around the kiln. The heat balance was first performed assuming that there were no heat losses. This yielded the heat input needed to raise the feed soil to the required temperature. Subsequently this heat input was increased by 20 percent to account for heat losses through the walls of the kiln. These heat losses are typical of those observed in the cement industry, where large-scale kilns are used. The revised heat input was then used to calculate combustion air and fuel rates.
- (c) The heat balance equations also assume that there is no heat required for melting the soil and additives. This simplifying assumption was made, at this time because no lab test data are available for the kaolin/soil mixture assumed for this study. This information would be developed during the R&D program. The net effect of this assumption is to underestimate the heat requirements slightly.
- (d) The heat balance equations are as follows:

Without Heat Loss

Enthalpy of Soil and Kaolin at 70°F (moisture excluded)	Enthalpy of Soil Moisture at 70°F	Enthalpy of Combustion air at 70°F	Heat Input (heating value of fuel)
H_s	H_M	H_A	H_F
	Enthalpy of Slag at 2,500°F	Enthalpy of Combustion Gas at 700°F	Enthalpy of Water Vapor at 700°F
	H_P	H_C	H_W



Note:
 M = Mass
 H = Enthalpy

FIGURE 33. Heat and mass balance diagram for the rotary kiln.



With Heat Loss

Enthalpy of Soil and Kaolin (w/o moisture) at 70°F	Enthalpy of Soil Moisture at 70°F	Enthalpy of Combustion air at 70°F	Heat Input (heating value of fuel)
H_s	H_M	H_A	H_r
-	Enthalpy of Product at 2,500°F	Enthalpy of Combustion Gas at 700°F	Enthalpy of Water Vapor at 700°F
	H_p	H_c	H_w
+	Heat Loss		
	H_L		

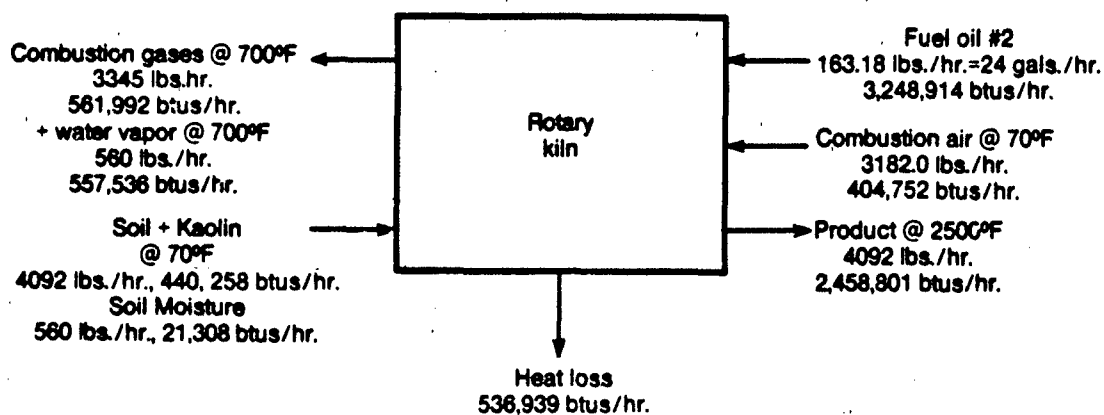
- (e) Physical properties such as specific heats, specific enthalpies etc. were obtained from standard references. The results of the heat and mass balances are summarized in Figure 34 for both the cases.
- (f) The mass balance equations assumed that there were no product losses in the kiln.

5.3.2.4 Major equipment. Processing and materials handling equipment were first chosen for the treatment of soil contaminated with metals (see Figures 29 and 30). As indicated in Section 4, the design was based on an on-site unit. However, maximum consideration was given to using mobile or transportable equipment, where it is currently available, to make it easier to relocate the process. Based on the process design requirements for length and diameter it was determined that the rotary kilns for both processing rates would be too large for truck mounted units. The kilns could, however, be dismantled, transported and re-assembled at another location.

Portable material handling equipment was available for this process. It was found that the same equipment could be used for both soil throughput cases (i.e., 10,000 and 100,000 TPY soil). The materials handling equipment for the 100,000 TPY case is the minimum size available. Therefore, the major difference in equipment for the two cases is the rotary kiln.

Equipment was chosen for this process on the basis of engineering analysis and conversations with equipment vendors.^{7,9,10} The following is a list of major equipment for both cases:

Case 1: 10,000 TPY soil



Case 2: 100,000 TPY soil

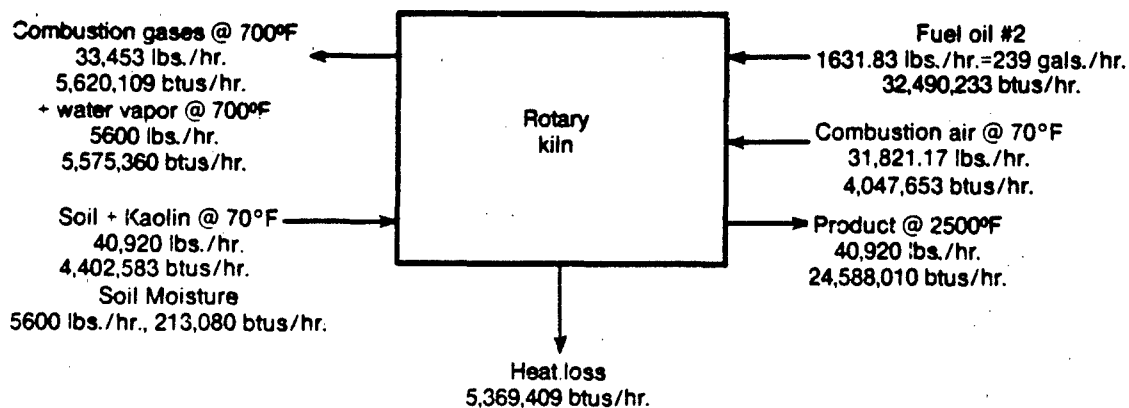


FIGURE 34. Summary of heat mass balances around the rotary kiln for roasting.



Number	Description	Purpose
<u>Case 1 - 10,000 TPY Soil -</u>		
1	Rotary kiln with grate cooler, belt conveyor, burner 2.5 tph-6.5 dia. x 90' length	To roast a mixture of soil and kaolin for making a nonleachable product.
	ID fan and baghouse	Dust control
<u>Case 2 - 100,000 TPY Soil -</u>		
2	Rotary kiln with grate cooler, belt conveyor, burner 25 tph-12.5' dia. x 195' length	To roast a mixture of soil and kaolin for making a nonleachable slag.
	ID fan, and bag-house	Particulate control.
<u>Equipment Common to both Cases:</u>		
3	Jaw Crusher (inlet particle size diameter <10")	Size reduction of cooled slag.
4	Portable conveyor 24" width x 50' length with a feed hopper, a one-way sloped grizzly at the bottom end and a trommel with 2" openings at the top.	Removing large rocks and debris and screening out over-size material. Screened soil is stockpiled for subsequent processing.
5	Portable conveyor 24" width x 50' length with two regulated belt feeders and hoppers at the bottom end and a twin shaft pug-mill mixer at the top end.	Mixing of the screened soil and kaolin prior to feeding to the kiln.
6	50,000 gal above-ground storage tank - carbon steel - 12 feet diameter	Storage of No. 2 fuel oil, used to fire kiln burner.



It must be noted that all the portable equipment is diesel-powered to enable remote site operation.

As indicated in Subsection 5.3.2.2, soils which are contaminated with both VOC's and metals would be first stripped of VOC's using an LTTS unit developed for USATHAMA. This unit consists of hollow screws which are used to heat and move the soil. The screw action can be used to mix the soil with kaolin thereby eliminating the need for a separate pugmill mixer unit. The VOC's stripped in the LTTS unit would be sent to the kiln as combustion air, where the organics would be destroyed, thereby eliminating the afterburner from the LTTS unit.

Specifications for the LTTS unit were taken from an earlier report by WESTON to USATHAMA on the treatment of soils contaminated by VOC's.¹² The rotary kilns, jaw crusher, screening/conveying and fuel oil storage equipment would be the same as that used in the treatment of soils contaminated with metals only. The following is a listing of the additional equipment needed for the treatment of soil contaminated with metals and VOC's used in place of equipment component No. 5 in the aforementioned listing.

Number	Description	Purpose
<u>Case 1 - 10,000 TPY Soil</u>		
1	HOLOFLITE® Thermal Processor Model NO. D-2424-6 with 2 screws, hot oil system, air preheater system and feed hoppers	To strip VOC's from the soil and mix kaolin with the soil.
<u>Case 2 - 100,000 TPY Soil</u>		
2	HOLOFLITE® Thermal Processor Model No. D-2424-6 with 4 screws, hot oil system, air preheater and feed hoppers	To strip VOC's from the soil and mix kaolin with the soil.
<u>Equipment common to both cases</u>		
3	Portable conveyor 24' width x 60' length with a gravity feed hopper at the bottom	To transfer the soil mixed with kaolin from the HOLOFLITE processor to the rotary kiln.



5.3.3 Cost estimates. Concept-level cost estimates were first developed for treatment of soils contaminated with metals only for the design basis given in Subsection 5.1 and the process described in Subsection 5.3.2.2. Subsequently, cost estimates for treatment of soils contaminated with VOC's and metals were developed using the data given in an earlier WESTON study for USATHAMA on low temperatures thermal treatment of soils to remove VOC's.¹¹ These cost estimates included both capital and operating costs. Budget prices were obtained from vendors for the major equipment. Unit costs for labor, equipment rental, and utilities were presented in Subsection 5.1.3.

As indicated in Subsection 5.1, costs associated with specific process siting, such as long utility connections and soil transportation to a central treatment site, were not calculated for all three technologies. Utility costs like electricity and water were not calculated for this technology since they are not major cost factors. However, fuel and raw material costs, which are significant in this process, were calculated. The following raw material unit costs were assumed:

Description	Unit Cost
Kaolin (spray dried clay)	\$10/ton

The cost obtained for kaolin was F.O.B., Sandersville, Georgia.¹⁰ An approximate transportation and handling charge was added to arrive at a unit cost for a hypothetical site.

In calculating the capital costs for the process, it was assumed that the transportation and installation costs for the rotary kiln (and appurtenances thereof) would be 100 percent of the base equipment cost. Equipment costs were based on estimated costs obtained from suppliers. Table 12 contains a breakdown of the total costs for the treatment of soils contaminated with metals only for both cases (i.e., 10,000 and 100,000 TPY soil). Table 13 is a similar breakdown for the treatment of soils contaminated with VOC's and metals. It should be noted that these are concept level estimates which are to be used for comparative purposes only. There is a considerable amount of process development and optimization which remains to be completed.



TABLE 12. ESTIMATED TOTAL PROJECT COSTS FOR TREATMENT
OF SOILS CONTAMINATED WITH METALS ONLY BY ROASTING

Item	Case 1	Case 2
	10,000 TPY (Dollars)	100,000 TPY (Dollars)
<u>Capital (Includes</u> <u>Transportation and Installation</u>		
Rotary Kiln, Cooler, and Other Appurtenances	2,000,000	3,400,000
Soil Screening, Handling, Conveying, and Other Ancillary Equipment	<u>200,000</u>	<u>200,000</u>
Subtotal	2,200,000	3,600,000
<u>Operations and Maintenance</u>		
Labor	1,280,000	1,580,000
Equipment Rental	345,000	425,000
Raw Materials and Major Utilities	<u>295,000</u>	<u>2,435,000</u>
Subtotal	1,920,000	4,440,000
<u>Technology Implementation</u>		
Designs, Plans, Specifications, and Regulatory Approval -20% of Capital	440,000	720,000
Contingency at 25% of Summed Up Costs for Capital, O&M and Implementation	<u>1,140,000</u>	<u>2,190,000</u>
Total Project Cost	5,700,000	10,950,000



TABLE 13. ESTIMATED TOTAL PROJECT COSTS FOR TREATMENT
OF SOILS CONTAMINATED WITH VOC's AND METALS - LTTS
FOLLOWED BY ROASTING

Item	Case 1	Case 2
	10,000 TPY (Dollars)	100,000 TPY (Dollars)
<u>Capital (Includes</u> <u>Transportation and Installation</u>		
Rotary Kiln, Cooler, and Other Appurtenances	2,000,000	3,400,000
HOLOFLITE® Processor (LTTS Unit) and Appurtenances	670,000	1,630,000
Soil Screening, Handling, Conveying, and Other Ancillary Equipment	<u>200,000</u>	<u>200,000</u>
Subtotal	2,870,000	5,230,000
<u>Operations and Maintenance</u>		
Labor	1,405,000	2,050,000
Equipment Rental	345,000	425,000
Raw Materials and Major Utilities	<u>455,000</u>	<u>3,485,000</u>
Subtotal	2,205,000	5,960,000
<u>Technology Implementation</u>		
Designs, Plans, Specifications, and Regulatory Approval -20% of Capital	575,000	1,046,000
<u>Contingency at 25% of Summed</u> <u>Up Costs for Capital, O&M and</u> <u>Implementation</u>	<u>1,413,000</u>	<u>3,059,000</u>
Total Project Cost	7,063,000	15,295,000



These tables show that the 100,000-TPY soil processing rate is more cost-effective. This is because the capital and installation costs for the rotary kiln are the most significant components of the total project cost. The capital and installation costs for a kiln for a 100,000-TPY soil processing rate are only twice those for a 10,000 TPY-soil processing rate. Therefore, for a 10 time increase in the soil processing rate, the capital cost goes up by only a factor of two. The operating costs are slightly sensitive to the operating temperature as higher operating temperatures mean higher fuel costs.

5.3.4 Requirements for development.

5.3.4.1 Data gaps. The following primary data gaps were identified for the roasting technology:

- (a) Determine optimal types of additives.
- (b) Determine optimal ratio of soils to additives.
- (c) Determine necessary processing temperature.
- (d) Confirm nonleachable characteristics of slag.
- (e) Determine the impact of soil type on system performance including:
 - Percent oversize.
 - Moisture content.
 - Particle size distribution.
 - Clay, silt and sand content.
- (f) Determine pilot and full-scale operational data including feed and product rates, cycle times, down times, product handling requirements, heat and mass balances, temperature profiles, etc.

5.3.4.2 Development program outline. Based on the above data gaps, the following is a preliminary outline for a Roasting developmental program:

- (a) Laboratory program to determine:
 - Effective type of additive (kaolin types or other additives): Hold temperature constant and vary additive or kaolin type for a given ratio.
 - Effective soil-to-additive ratio: Vary ratio, keeping temperature constant.
 - Required process temperature: Keep ratio of soil to additive constant; vary temperatures.
 - Effect of soil type: Test 2 to 3 divergent soil types.
 - Criterion for establishing all of the above parameters is that the product should be nonhazardous per the TCLP and EP Toxicity tests.



(b) Pilot scale test program to establish:

- Fate of organic constituents with countercurrent and concurrent operation.
- Operating parameters such as kiln speed, burner temperature, exit gas temperature and baghouse performance.
- Heat and mass balances.
- Fuel requirements.
- Product quality-EP Toxicity tests.
- Refine cost estimates.

5.3.4.3 Estimated development costs. Preliminary costs for the above developmental program were estimated. It must be noted that these estimates will be revised when the actual laboratory program/plan is written. The range of the estimated costs for the laboratory developmental program is \$60,000-\$180,000.

Costs for the other phases of the developmental program cannot be estimated at this time because they would be based on the outcome of the laboratory program.

5.3.5 References

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10. Personal Communications with Mr. Barnaby, Pennsylvania Crusher, Broomall, Pennsylvania, October 1986.
11. Personal communications with Mr. Bob Timko, Thiele Kaolin Company, Sandersville, Georgia, October 1986.
12. Draft Technical Report on Economic Evaluation of Alternative Options for Low Temperature Thermal Stripping of Volatile Organic Compounds from Soil, prepared by WESTON under contract to USATHAMA, June 1986.

5.4 On-Site Extraction

5.4.1 Description. The extraction process would involve excavation of the soil and treating it with one or more chemical wash solutions to remove metals. The wash solution (containing the extracted contaminants) would be treated further to remove the contaminants and the treated solution would be recycled back into the process for continued washings or discharged. The number of washes, soil/solution ratios, and other process requirements are determined by site-specific conditions such as soil type, metals present, metal species, etc. The mechanisms for contaminant transfer to the solution phase include solubility, formation of an emulsion or soluble chelation product, and chemical reaction.

Solvent extraction is used extensively in the chemical process and metallurgical industries. In the latter industry, extensive work has been done on the recovery of metals from ore as well as metals recovery from metallurgical operations waste. There has been extensive study using an extraction process for treating metal plating waste water followed by selective recovery by precipitation and/or extraction. There is a strong incentive for metallurgical and plating industries to find methods to treat their metal bearing wastes since disposal costs are high and valuable metals are being lost.

There is recent literature available on the applicability of this process to metal contaminated soils. Investigations range from experimental to field applications. Several solutions/methods have been studied to extract metals from soils. Subsection 3.11 discusses these methods used for extracting metals from wastes.^{1,2,3,4,5,6} Among the above methods, reaction by acidification and/or chelation appear to be the best technique for extraction of metals from soils as they appear to have a higher removal efficiency. This section will focus on these techniques.

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Both strong and weak acid solutions have been used in the metallurgical industry to extract metals. Acid solutions dissolve basic metal salts like hydroxides, oxides and carbonates. Using strong acid solutions to treat soils may present problems because of potential hazardous residues left in the soil or alterations of soil physical properties. Soils with sufficient alkalinity to buffer acids may be treated with a dilute solution of a strong acid like H_2SO_4 ; otherwise weak acids like acetic acid may be preferred. In one experiment, municipal sludge was treated with sulfuric acid to extract a range of heavy metals.² With the exception of Pb, all the heavy metals (Fe, Al, Zn, Mg, Ca, Ni, Ar, Cr, and Mn) were extracted to some degree by H_2SO_4 . The extracted solution was then treated with lime to alter the pH and precipitate the metals. A similar acid extraction process has been proposed for treatment of plating sludge at USATHAMA with selective precipitation and extraction for metal recovery.³ Recovery of metals is less cost effective at lower concentrations, especially when there is a mixture of metals which may be difficult to separate.

Ethylene-diamine-tetracetic acid (EDTA) is a chelating agent which forms a metal-chelate complex when reacted with metals. These complexes are resistant to decomposition and degradation and can be used as a means of extracting metals from soil. Other chemicals/agents include citric acid and diethylenetriamine-pentacetic acid (DTPA).

Upon reacting with metals, these agents form complexes, which are soluble in water. The extract is treated to concentrate or recover the metals. The chelating agent would be recycled for cost-effective treatment.

In some soils metals are strongly adsorbed by the magnesium and iron oxides in the soil and extraction with just a chelating agent is not sufficient. In such instances, the metal oxides are first reduced and then mobilized into solution. This is accomplished by adding treatment agents like hydroxylamine and sodium dithionite/citrate along with EDTA.⁴

Bench-scale experimental work by researchers in the field^{7,8,9} indicates that EDTA is an effective metal chelating agent which can be used to remove metals from soils. EPA developed a mobile soil washing system based on this initial experimental work.^{10,11} In this system, oversize nonsoil material and debris is first screened out of the excavated soil. Subsequently, the soil is washed/scrubbed in a rotary drum screen. The soil is then treated with the extract solution in a four-stage counter current chemical extractor to remove the metals. The soil slurry is sent to a clarifier where the solids and solution are separated, with the soils being disposed and the solution treated so that it can be recycled into the washing and extraction stages.



EPA conducted a pilot study at a Leeds, Alabama site where the soil was contaminated with lead. Personal communications with Richard P. Traver of the EPA's Hazardous Waste Engineering Research Laboratory, Releases Control Branch, Edison, New Jersey indicated that a 13-percent EDTA solution was used as an extracting solution in the test.¹² The spent extracting solution was treated with sodium sulfite to remove lead and the solution was then recycled to the system. The test results indicate that even though the process achieved 90-percent (Pb) removal, it was unsuccessful in reaching the desired target of EP Toxicity test levels for lead in the extract from the treated soil.¹²

Similarly, other field tests at a Wisconsin Superfund site showed that the process was only partially successful in treating high concentration lead-contaminated soil and wastes. The conclusion drawn from all these tests was that the process may only be effective in treating soils with lower levels of lead contamination. In addition, serious material handling problems were experienced during these field tests. Additional research and development work would be necessary to resolve many of these problems.

Due to the problems/concerns associated with the EDTA process, a search was initiated to see if there were any commercial, full-scale processes which were available in the market for treatment of metal contaminated soils. This search revealed that MTA Remedial Resources, Inc. (MTARRI) had developed a system on a conceptual basis for extracting metals from contaminated soil based on their experience in the mining and extractive metallurgy industry. Subsequently, MTARRI was contacted to obtain details of their process.¹³

The first step in the MTARRI extraction process is a leach tank where the soils are mixed with an aqueous mixture of acids. After providing sufficient contact time to allow the metals to be solubilized, the soil is successively washed in thickeners to remove the aqueous phase metals. The flow of water and soil in the washing stages is counter-current. This washing technique is used extensively in the mining industry and is called counter-current decantation. After the soil has been washed in the thickeners to remove the aqueous phase metals, it is dewatered and can be disposed in either the excavated area or an approved landfill.

The overflow extract solution from the first thickener is treated to remove the metals and recycled to the last thickener/washer. This treatment process yields a metal bearing sludge which would have to be disposed appropriately.



MTARRI has reportedly conducted laboratory tests which show that high removal efficiencies are possible with this process. The critical assumption utilized in their process configuration is that complete or near complete solubilization of the metal species (or leachable metal species) will occur in the leach tank. The specific soil types, metal species, extract composition, operating conditions, and results which they have used to demonstrate this are not available. However, based on the success of the acid leach processes in the metallurgical industry, the availability of demonstrated metallurgical process equipment, the use of acidic leaching in the EP Toxicity procedure, and the lower cost of the acid extract reagents compared to chelating agents, the acid leaching/washing process should have higher potential for providing cost-effective soil treatment than the EDTA washing process tested by EPA. As a result, the acid leaching/washing process was used in the conceptual design.

MTARRI recommends using the phosphate precipitation process, which is in itself an emerging technology, for treating the extract solution.¹³ There are several advantages cited by MTARRI for using this new process, including precipitation in an acidic environment and rapid settling of the metal precipitate. Acidic precipitation will allow treatment and reuse of the solution with little expensive pH adjustment. However, Dahnke, et al¹⁴, in a paper on the phosphate precipitation processes indicated that the process could not be used to simultaneously remove Cr, Cd, and Pb from wastewater. In fact, the process appears to be most useful for the sequential recovery of metals at different pH levels. The intended application has been the selective recovery of metals from ores. Since the technology conceptual design should be suitable for treating extraction solutions containing Cr, Cd, and Pb, phosphate precipitation was not considered appropriate.

The choice of the technology used to treat metal-laden water will depend on the results of the process optimization studies, which should be conducted before the implementation of the full-scale process. For the purpose of this analysis, approximate costs for conventional metal precipitation processes will be used.



EPA publications^{19,20} indicate that the most common methods used in industry for treating metals contaminated wastewater are the hydroxide and sulfide precipitation process. There are two sulfide precipitation process namely the insoluble sulfide process called SULFEX (patented by Permutit) and the traditional soluble sulfide process which uses NaHS to precipitate the metals. There are several advantages and disadvantages associated with each of these processes. Hydroxide precipitation is effective in removing metals to a moderately low final concentration but the treated effluent may not meet the most stringent discharge requirements. The other disadvantage is that the metal hydroxide precipitate resolubilizes to some extent if the pH of the solution varies during operation. The soluble sulfide precipitation process on the other hand yields an effluent with very low metal concentrations and performance is less sensitive to variations in pH. However, since NaHS is used, pH must be precisely controlled to prevent H₂S emissions and is not as effective as hydroxide precipitation for Cr removal. The insoluble sulfide (SULFEX) process does not have the problem with H₂S emissions but the amount of sludge generated is higher than that in other processes.

Based on a review of these documents, it appeared that a combination of hydroxide precipitation with the SULFEX process would have the highest probability of meeting the range of potential requirements of the on-site extraction technology. Accordingly, a phone conversation was initiated with the Permutit Company²¹ to obtain more information on the SULFEX process. After reviewing the anticipated requirements of the on-site extraction technology, Permutit indicated that it could supply a combined two-stage process to treat the wastewater.

5.4.2 Conceptual design.

5.4.2.1 Assumptions. The following conditions/assumptions were used in developing the concept design for extraction:

- (a) The basic soil leaching/washing contacting scheme used by MTARRI will be employed in the process.¹³ This would include a leach tank followed by a 5 stage counter-current decantation system. The washing and settling of the soil particles will be accomplished in gravity thickeners.
- (b) The metals (or leachable fraction of metals) will be completely leached into the aqueous phase in the leach tank. In the subsequent thickening/washing stages, the metals will be present only in the aqueous phase.
- (c) In all the thickeners, the ratio of the wash water feed rate to the solids feed rate will be 3:1 by weight. The solids concentration in the underflow from each thickener will be 50 percent.



- (d) The contact/residence time in the leach tank will be approximately 2.5 hours.
- (e) High rate thickeners will be used in the process. A conservative solids separation rate of 2 sq ft/ton/day was used to size the thickeners. This choice was based on actual operational data supplied by Enviro-Clear, Inc. for metallurgical applications.¹³
- (f) The high rate thickeners will require polymer addition for flocculation of solids. The flocculated slurry will be fed horizontally into the active settling zone which then acts as a filter. This arrangement will yield a high settling rate.
- (g) The design and the material balances assume that there will be negligible solids overflow in the entire system.
- (h) The system was assumed to be in operation for 330 days/year, 24 hrs/day.
- (i) The actual dosage of reagents (acids) that must be added to leach the metals from the soil will vary from site to site. MTARRI provided approximate reagent costs but did not include details on the addition of reagents. The material balances were calculated without specifically accounting for the added mass of solution from the reagents. This reagent solution mass may be substituted for a portion of the feed water, however, without significantly altering the overall material balances. Since specific additives and dosages remain to be determined in a development program, the estimated additive costs cited by MTARRI were used in this evaluation.
- (j) The overflow from the first thickener will be treated to remove metals. The treated water will be mixed with make-up water and returned to thickener No. 5. Presently, the choice of water technology is secondary to the development of a successful extraction process. The selection of a water treatment approach should be based on the outcome of process development and optimization. For the purpose of this analysis, approximate costs for conventional metal precipitation processes will be used based on published literature.
- (k) Hydroxide precipitation will be used to remove more than 90 percent of the influent metals. The SULFEX process will be used for polishing.
- (l) Sodium hydroxide will be used to provide maximum reliability. Sodium hydroxide requirements will be approximately 1.25 times the stoichiometric requirements for Cr, Cd, and Pb.
- (m) Fe_2S requirements for polishing will be 25 lb/day for the 100,000 TPY case and 2.5 lbs/day for 10,000 TPY.²¹



- (n) Sludge quantities generated will be 1.25 times for stoichiometric quantity based on Cr, Cd, and Pb hydroxide precipitation to account for other extracted soil minerals or metals.
- (o) The dewatered sludge will contain 30 percent solids at a density of 65 lbs/cu ft.
- (p) The sludge disposal site will be 500 miles from the installation. This disposal site would be a secure landfill which is permitted under RCRA to accept hazardous wastes.

5.4.2.2 Flow sheets. Figure 35 and 36 are the block flow diagrams for the treatment of soils contaminated with metals only, and for treatment of soils contaminated with VOC's and metals, respectively. As in the case of roasting and microencapsulation, it was assumed that in the treatment of soils contaminated with VOC's and metals, VOC's first would be removed from the soil by LTTS. Subsequently, the soil would be treated with acids to remove the metals. The VOC's which are stripped from the soil would be combusted prior to discharge to the atmosphere. Unlike roasting and microencapsulation, however, the LTTS does not replace major process functions (e.g., mixing, heating, or drying) upon integration in an overall process. This also would be true of a combined explosives incineration/metals extraction process. Figures 37 and 38 are flow diagrams with major equipment for the treatment of soils contaminated with metals only and soils contaminated with VOC's and metals, respectively.

It should be noted that there may be other options available for the treatment of soils to remove VOC's. LTTS is presented here for informational purposes only because current cost data is available. The next section on material balances deals primarily with the treatment of soils contaminated with metals. Subsequent sections on major equipment and costs, also deal mainly with soils contaminated with metals only.

5.4.2.3 Material balances. Material balances were developed for the extraction of metals from soils for both the soil processing rates (10,000 TPY and 100,000 TPY). In developing these balances the following conditions/assumptions, in addition to those in 5.4.2.1, were used:

- (a) Input soil metal concentrations were:

- Cd - 500 mg/kg
- Cr - 3,000 mg/kg
- Pb - 5,000 mg/kg

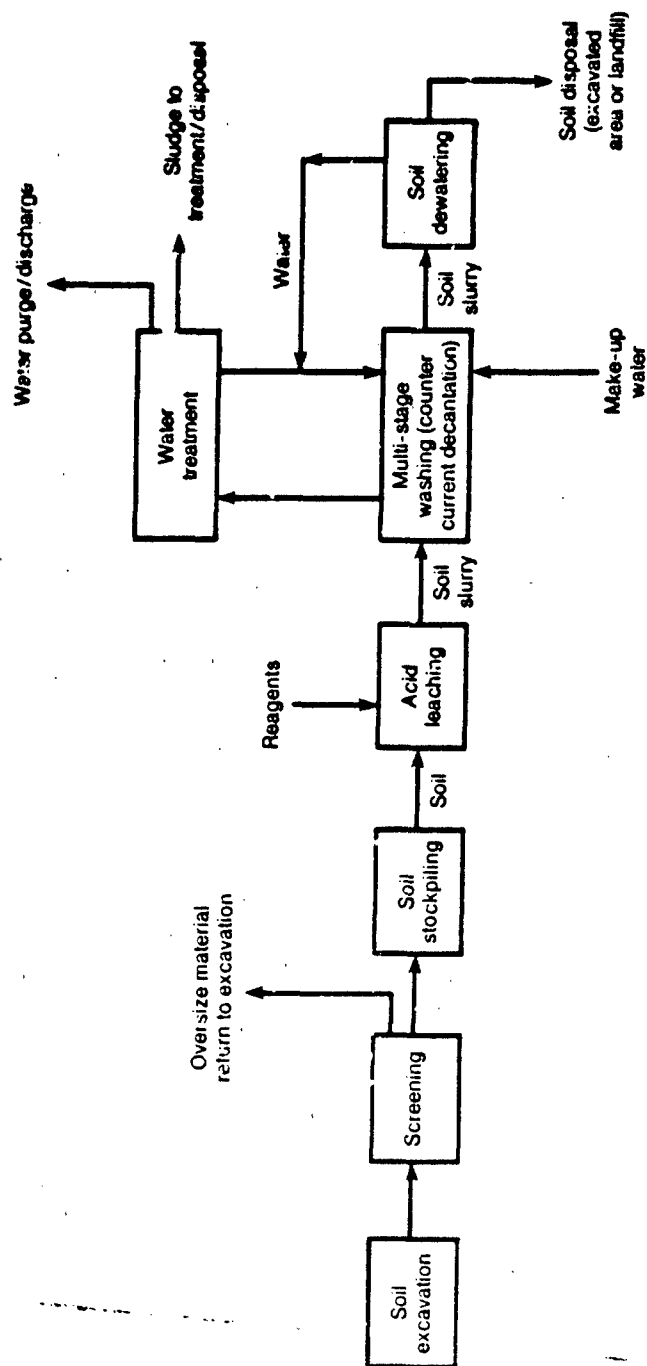


FIGURE 35. Block flow diagram for the treatment of soils contaminated with metals only - by extraction.

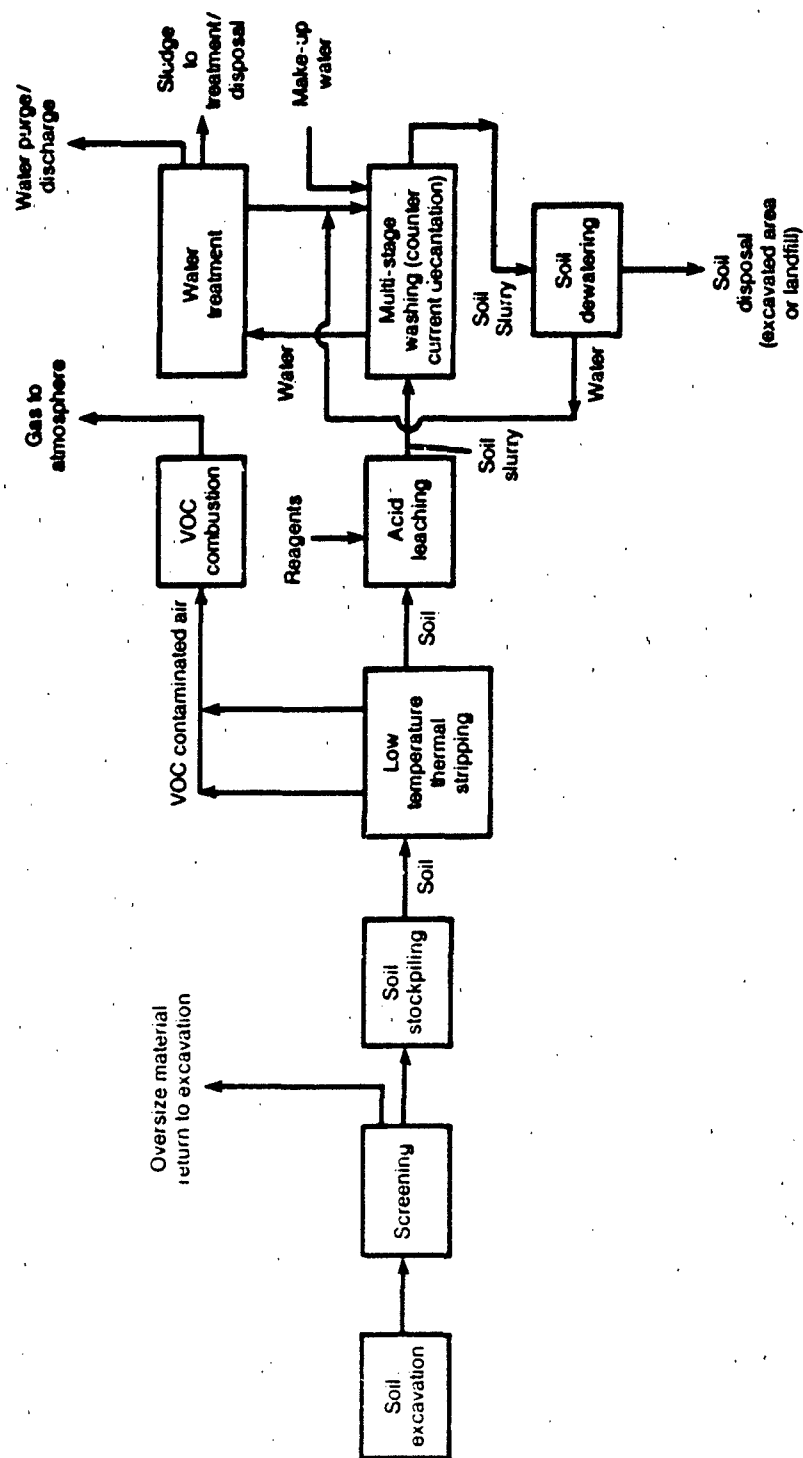


FIGURE 36. Block flow diagram for the treatment of soils contaminated with VOC's and metals — Low-Temperature Thermal Stripping followed by extraction.

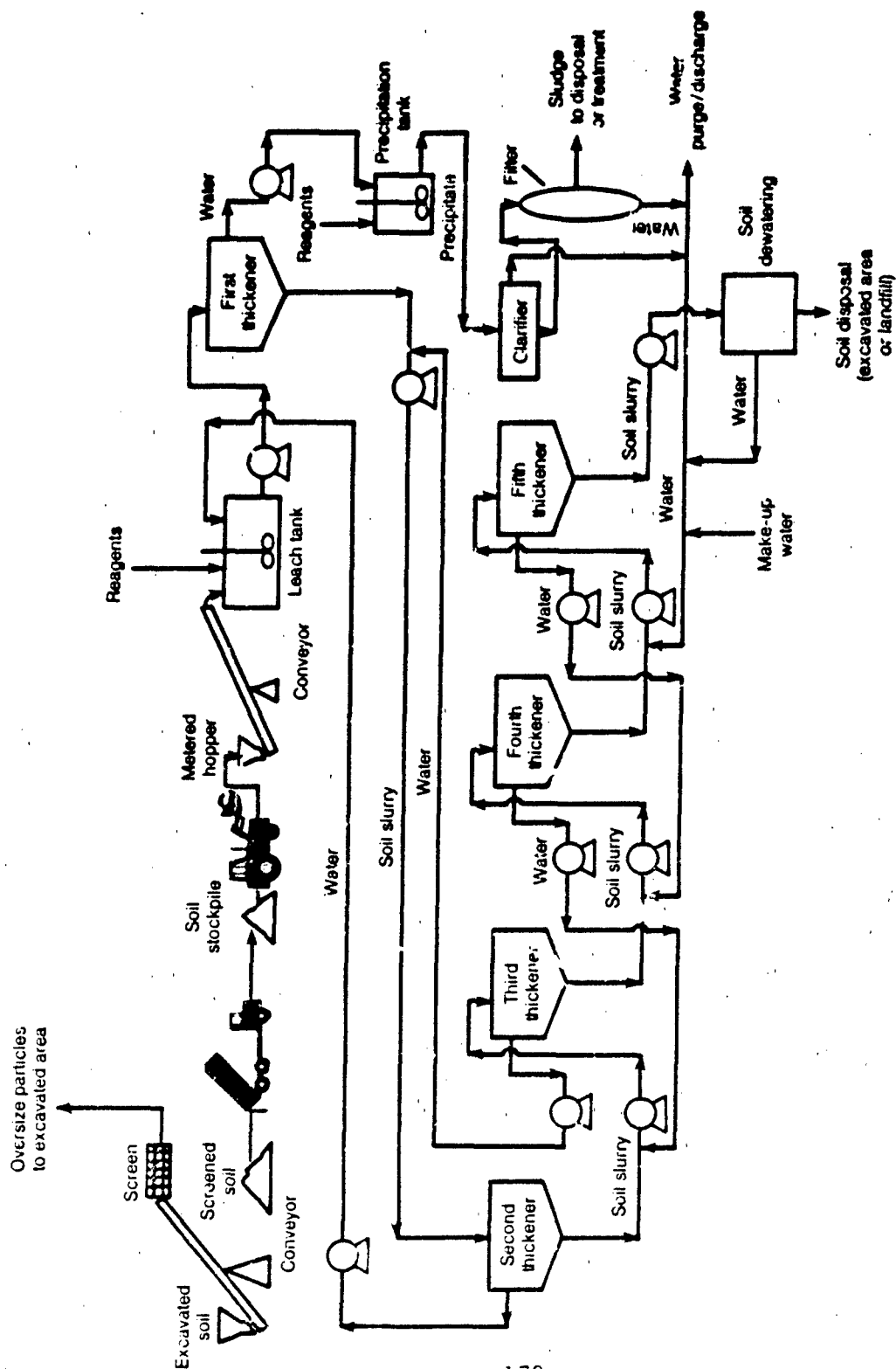


FIGURE 37. Flow diagram with major equipment for the treatment of soils contaminated with metals only - by extraction.



These concentrations represent the maximum of the range of concentrations used as the design basis. The maximum concentrations were used in determining the number of washing stages and extract solution addition rates as well as the material balances for treating soil from a generic site.¹³

- b. Since the input soil concentrations and the ratio of soil to water in the thickeners is the same, it was assumed that the metal concentrations at various stages in the process would be the same as those generated by MTARRI.

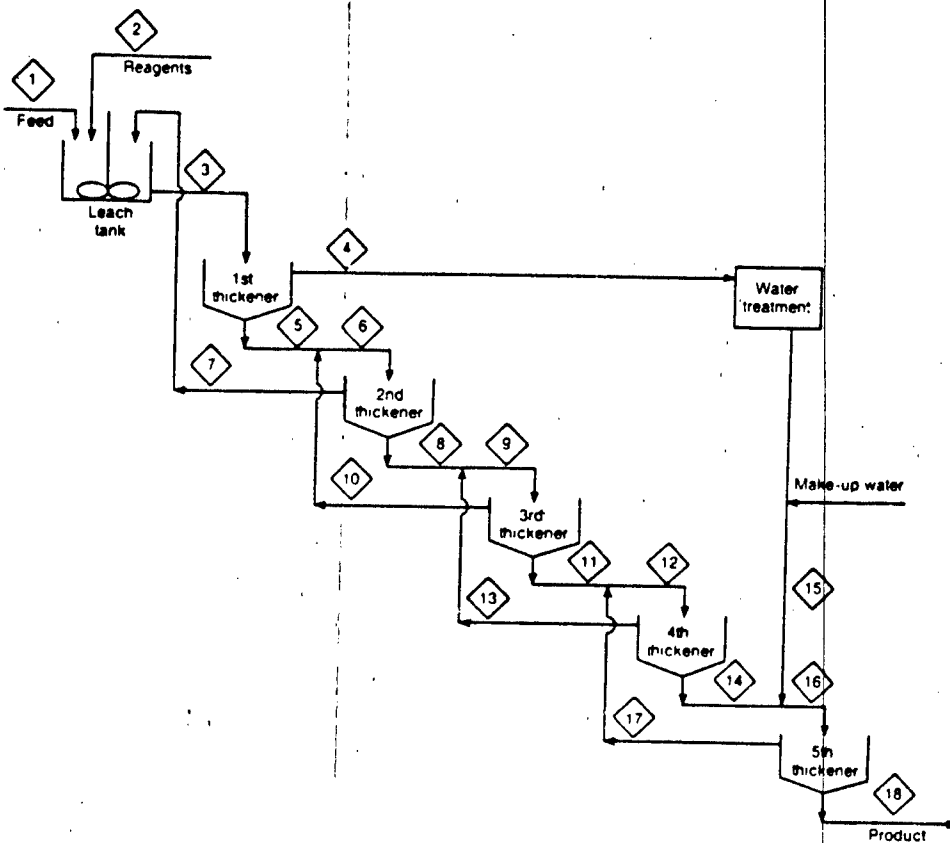
Figures 39 and 40 show the material balances for the treatment of 10,000 TPY and 100,000 TPY of soil, respectively. These figures contain a tabulation of all the numerical values for the various streams and a diagram showing the stream numbers and locations.

5.4.2.4 Major equipment. As indicated in Subsection 5.1, the concept design was based on an on-site unit with consideration being given to the mobility of the equipment. Equipment was chosen based on engineering analysis and discussion with vendors who were familiar with the handling and processing of large quantities of soil (e.g., mining industry applications).^{15,16,17} Based on the volume and size requirements, it was determined that the thickeners or the leach tank could not be truck-mounted units. However, for the smaller soil processing rate (10,000 TPY), the units could be moved by truck from one site to another without any dismantling. The larger units required for the higher soil processing rate (100,000 TPY) could be of the bolted construction type which means they can be disassembled and transported from one site to another and reassembled. The following is a listing of major equipment required for both cases, for treatment of soils contaminated with metals only.

No	Description	Quantity	Purpose
<u>Case 1 - 10,000 TPY Soil</u>			
1	Portable conveyor 24 in. (width) x 50 ft (length) with a gravity hopper and grizzly at the bottom end and a 2 inch opening trommel at the top.	1	To screen out oversize material such as rocks and other debris.

MATERIAL BALANCE

STREAM NO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
DESCRIPTION	Sol Feed	Reagents	Leach Tank UF - Sol Slurry Feed to First Thickener	First Thickener OF	First Thickener UF	Sol Slurry - Feed to Second Thickener	Second Thickener OF	Second Thickener UF	Sol Slurry - Feed to Third Thickener	Third Thickener OF	Third Thickener UF	Sol Slurry - Feed to Fourth Thickener	Fourth Thickener OF	Fourth Thickener UF	Treated Water Make-up	Sol Slurry - Feed to Fifth Thickener	FB Tr-12 OF
Slurry																	
lbs/day (thousands)	60.6		206.1		97	242.5		97	97		97	242.5		97		242.5	
Cd - lbs/day																	
Cr - lbs/day																	
Pb - lbs/day																	
Solids																	
lbs/day (thousands)	48.5		48.5		48.5	48.5		48.5	48.5		48.5	48.5		48.5		48.5	
Cd - ppm	500																
lbs/day	24																
Cr - ppm	3000																
lbs/day	145																
Pb - ppm	5000																
lbs/day	242																
Solution																	
lbs/day (thousands)	12.1		157.6	109.1	48.5	194	145.5	48.5	194	145.5	48.5	194	145.5	48.5	145.5	194	145
Cd - ppm	--		222	222	222	73	73	73	23	23	23	7	7	7	--	2	2
lbs/day	--		35	24	11	142	10.6	3.6	4.5	3.3	1.2	1.4	1.0	0.4	--	0.4	0.4
Cr - ppm	--		1329	1329	1329	439	439	439	140	140	140	43	43	43	--	11	11
lbs/day	--		209.4	145	64.4	85	64	21	27	20	7	8	6	2	--	2.1	1.1
Pb - ppm	--		2215	2215	2215	732	732	732	234	234	234	71	71	71	--	18	18
lbs/day	--		349	242	107	142	106	36	45	34	11	14	10	4	--	3.5	2.1



NOTES: (1) Represents maximum soil concentrations and soil solubilization in the leach tank.

FIGURE 39. Material balance for extraction of metals from soils for case 1 - 10,000 TPY soil.

MATERIAL BALANCE

STREAM NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
DESCRIPTION	Slurry Feed	Residuals	Leach Tank UF - Slurry Feed to First Thickener	First Thickener OF	First Thickener UF	Slurry Feed to Second Thickener	Second Thickener OF	Second Thickener UF	Slurry Feed to Third Thickener	Third Thickener OF	Third Thickener UF	Slurry Feed to Fourth Thickener	Fourth Thickener OF	Fourth Thickener UF	Treated Water Make-up	Slurry Feed to Filtrate
Slurry																
lbs./day (thousands)	606		2061		970	2424		970	2424		970	2424		970		2424
Cd - lbs./day																
Cr - lbs./day																
Pb - lbs./day																
ds																
lbs./day (thousands)	485		485		485	485		485	485		485	485		485		485
Cd - ppm	500		-													
- lbs./day	242		-													
Cr - ppm	3000		-													
- lbs./day	1450		-													
Pb - ppm	5000		-													
- lbs./day	2424		-													
on																
day (thousands)	121		1576	1091	485	1939	1454	485	1939	1454	485	1939	1454	485	1454	1939
d - ppm	--		222	222	222	73	73	73	23	23	23	7	7	7	-	2
- lbs./day	--		350	242	108	142	106	36	45	34	11	14	10	4	-	4
- ppm	--		1329	1329	1329	439	439	439	140	140	140	43	43	43	-	11
- lbs./day	--		2094	1450	644	852	639	213	272	204	68	83	62	21	-	21
- ppm	--		2215	2215	2215	732	732	732	234	234	234	71	71	71	-	18
- lbs./day	--		3490	2416	1074	1420	1065	355	454	340	114	138	103	35	-	35

No.	Description	Quantity	Purpose
2	Leach Tank - 2,500 gallon reactor with a 3 hp motor and mixer at 56 rpm - rubber covered steel moving parts.	1	To leach all the metals from the soil into the acid solution.
3	Enviro-Clear high-rate high-loading thickeners - 8 feet in diameter.	5	To wash and settle the soil in order to remove the aquerous phase metals.
4	Underflow-slurry pumps and other water pumps.	6	To move the slurry from leach tank to the thickeners and from one thickener to another and to wash the soil in a counter-current mode.
5	SULFEX skid-mounted, two-stage package treatment. Includes pumps, piping, controls, filter press, etc. for 10 gpm.	1	To treat the wash solution overflowing the first thickener.
6	Caustic (NaOH) solution storage tank - 15,000 gallon	1	Caustic storage - not included in package treatment system.

Case 2 - 100,000 TPY Soil

7	Portable conveyor 24 in. (width) x 50 ft (length) and with a gravity grizzly at the bottom end and a 2 inch opening trommel at the top.	1	To screen out oversize particles such as rocks hopper and other debris.
8	Leach tank - 25,000 gallon reactor with a 10 hp motor and mixer at 30 rpm - rubber covered with steel moving parts.	1	To leach all the metals from the soil into the acid solution.

(Continued)

No.	Description	Quantity	Purpose
9	Enviro-Clear high-rate high-loading thickeners - 26 feet diameter.	5	To wash and settle the soil in order to remove the aqueous phase metals.
10	Underflow - slurry pumps and other water Pumps.	6	To move the soil from the leach tank to the thickeners and wash the soil in a counter-current mode.
11	SULFEX skid-mounted, two-stage package treatment system. Includes pumps, piping, controls, filter press, etc. for 100 gpm.	1	To treat the wash solutions overflowing the first thickener.
12	Caustic (NaOH) solution storage tank - 50,000 gallon	1	Caustic storage - not included in package treatment system.

It has been noted in Subsection 5.4.2.2 that soils which are contaminated with both VOC's and metals would first be treated in a (LTTS) unit to remove VOC's and subsequently treated with acids to remove metals. A brief description of LTTS is given in the earlier sections on the concept designs for the other two technologies. The following is a listing of the additional equipment needed for the treatment of soil contaminated with both metals and VOC's.

No.	Description	Quantity	Purpose
<u>Case 1 - 10,000 TPY Soil</u>			
1	HOLOFLITE® Thermal Processor Model No. D-2424-6 with 2 screws, hot oil system, and air preheater.	1	To strip VOC's from the excavated soil prior to extraction.
2	Afterburner - 5.0 feet inside diameter, 5 million Btu/hr burner size, 1,800°F - Exit gas temperature.	1	To combust VOC's in the stripped air.
<u>Case 2 - 100,000 TPY Soil</u>			
3	HOLOFLITE® Thermal Processor Model No. D-2424-6 with 4 screws, hot oil system, and air preheater.	1	To strip VOC's from the excavated soil prior to extraction.
4	Afterburner - 7.0 feet inside diameter, 15 million Btu/hr burner, 1,800°F - exit gas temperature.	1	To combust VOC's in the stripped air.
<u>Equipment Common to Both Cases</u>			
5	Portable conveyor 24 in. (width) x 60 ft (length) with a gravity feed hopper at the bottom.	1	To transfer the soil, which has been stripped as VOC's from the HOLOFLITE® processor to the leach tank.

5.4.3 Cost estimates. As in the previous Subsections (5.2 and 5.3) concept level cost estimates were first developed for the treatment of soils contaminated with metals and subsequently for the treatment of soils contaminated with VOC's and metals. The costs for the treatment of soils with metals only were developed using equipment costs obtained from vendors. The costs for LTTS of soils, for the removal of VOC's, were obtained from a previous study done by WESTON for USATHAMA on the same topic.¹⁸ Unit costs for labor, equipment rental, and utilities were presented in Subsection 5.1.3.

Other operating costs pertaining to extraction, such as reagent/chemicals and energy, were obtained from MTARRI's estimate.¹³ This estimate indicated that reagent costs would be approximately \$12.64/ton and power costs would be \$3.65/ton. While MTARRI estimated these costs using a 70-tpd throughput, it was assumed that these operating costs would be applicable to other soil processing rates (i.e., 10,000 and 100,000 TPY).

While the choice of a wastewater treatment technology and its operating conditions are difficult to project, the overall concept level cost estimate for implementing extraction would be incomplete without representing costs for wastewater treatment. Thus, the use of conventional wastewater treatment technology was assumed as described in the previous subsections. The following raw material and sludge disposal costs were assumed:

Description	Unit Cost
1. Caustic solution - 50 percent	\$200/dry ton
2. Caustic transportation	\$2/100 wt
3. Fe ₂ S - including delivery	\$0.50/lb
4. Sludge disposal (PCRA permitted facility)	\$160/cu yd
5. Sludge transportation	\$4/loaded mile

Table 14 summarizes the costs for both soil processing rates for the treatment of soils contaminated with metals only while Table 15 is a summary of these costs for the treatment of soils contaminated with metals and VOC's. These estimates were based on assumptions in this section and those in Subsection 5.1.

It should be noted that these are concept-level estimates which should be used for comparative purposes only. Many of the costs, particularly for reagent use and sludge disposal, will remain uncertain until further process development and process optimization is conducted.

These tables show that the higher 100,000-tpy soil processing rate becomes more cost-effective. The labor, equipment, and capital costs for the higher processing rate increase much more slowly than the processing rate itself resulting in significant economics of scale. The raw material and sludge disposal operating costs, which comprise a large fraction of the overall cost, are very sensitive to the concentration of metals in the contaminated soils.

**TABLE 14. ESTIMATED TOTAL PROJECT COSTS FOR TREATMENT
OF SOILS CONTAMINATED WITH METALS ONLY - BY EXTRACTION**

Item	Case 1	Case 2
	10,000 TPY (Dollars)	100,000 TPY (Dollars)
<u>Capital (Includes Transportation and Installation)</u>		
Leach Tank, Thickeners and Other Process* Equipment	342,000	1,177,000
Wastewater/Treatment System Equipment	250,000	405,000
Soil Screening, Handling, Conveying, and Other Ancillary Equipment	<u>88,000</u>	<u>88,000</u>
Subtotal	680,000	1,670,000
<u>Operations and Maintenance</u>		
Labor	1,335,000	1,485,000
Equipment Rental	265,000	265,000
Raw Materials and Major Utilities	1,144,000	2,865,000
Sludge Disposal	<u>118,000</u>	<u>1,180,000</u>
Subtotal	2,862,000	5,795,000
<u>Technology Implementation</u>		
Designs, Plans, Specifications, and Regulatory Approval Lump Sum Cost**	500,000	750,000
<u>Contingency at 25% of Summed Up Costs for Capital, O&M and Implementation</u>	<u>1,010,000</u>	<u>2,054,000</u>
Total Project Cost	5,052,000	10,269,000

*Does not include costs for treated soil dewatering equipment.

**This was not calculated as a percent of the capital cost as the estimated implementation costs would be higher due to the uncertainties in treatment performance.



TABLE 15. ESTIMATED TOTAL PROJECT COSTS FOR TREATMENT
OF SOILS CONTAMINATED WITH VOC's AND METALS - LTTS FOLLOWED
BY EXTRACTION

Item	Case 1	Case 2
	10,000 TPY (Dollars)	100,000 TPY (Dollars)
<u>Capital (Includes Transportation and Installation)</u>		
Leach Tank, Thickeners and Other Process* Equipment	342,000	1,177,000
Wastewater Treatment System Equipment	250,000	405,000
HOLOFLITE® Processor (LTTS Unit) and Appurtenances	670,000	1,630,000
Soil Screening, Handling, Conveying, and Other Ancillary Equipment	<u>88,000</u>	<u>88,000</u>
Subtotal	1,350,000	3,300,000
<u>Operations and Maintenance</u>		
Labor	1,459,000	1,958,000
Equipment Rental	265,000	265,000
Raw Materials and Major Utilities	1,359,000	4,539,000
Sludge Disposal	<u>118,000</u>	<u>1,180,000</u>
Subtotal	3,200,000	7,942,000
<u>Technology Implementation</u>		
Designs, Plans, Specifications, and Regulatory Approval Lump Sum Cost**	500,000	750,000
<u>Contingency at 25% of Summed Up Costs for Capital, O&M, Implemen- tation and Wastewater Treatment</u>	<u>1,263,000</u>	<u>2,998,000</u>
Total Project Cost	6,313,000	14,990,000

*Does not include costs for treated soil dewatering equipment.

**This was not calculated as a percent of the capital cost as
the estimated implementation costs would be higher due to the
uncertainties in treatment performance.

5.4.4 Requirements for development.

5.4.4.1 Data gaps. The following primary data gaps were identified for the extraction technology:

- (a) Effect of the type/nature of the soils (minerology, organics, or humic content, etc.) on process performance.
- (b) Effect of the type, form, and concentrations of the metal contaminants in the soils on process performance.
- (c) Choice of leaching/solubilizing agents/acids for extracting metals of concern and quantity required.
- (d) Effects of varying extractant concentrations and pH.
- (e) Reaction/contact time, necessary in the leach tank for complete solubilization.
- (f) Degree of solubilization in leach tank.
- (g) Treatment effectiveness and residual metal levels in treated soils.
- (h) Dewatering characteristics of treated soils.
- (i) Wastewater treatment system selection/operating conditions.
- (j) Process design.
- (k) Process optimization.

5.4.4.2 Developmental program outline. Based on the above data gaps, the following is a preliminary outline for an Extraction developmental program:

- (a) Laboratory program to establish:
 - The best leaching/solubilizing agent for different soil types.
 - Solubilizing/leaching efficiency for a given soil-leaching agent system.
 - Contact time in the leach tank.
 - Process to treat metal-laden wastewater.
- (b) Pilot Scale Testing Program, to establish:
 - Process parameters such as reaction time, number of wash stages, ratio of wash solution to soils, etc.
 - Scale-up factors for the full scale extraction process.
 - Optimal wastewater treatment process and associated scale-up factors.



5.4.4.3 Estimated development costs. As indicated in Subsections 5.2 and 5.3, preliminary costs were estimated for the development program. These estimates will be revised once the laboratory plans have been developed. The range of the estimated costs for the laboratory development program is \$40,000 to \$120,000. Costs for the other phases of the development program cannot be estimated at this time since they would be based on the outcome of the laboratory testing.

5.4.5 References

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6. TECHNOLOGY EVALUATION

This section describes the basis and the results of the detailed technical evaluation of each technology. The first subsection describes the criteria and the methodology used in performing the evaluation. Subsequently, the results of the evaluation of each technology are presented.

6.1 Criteria. The three technologies selected were evaluated on the basis of the following criteria:

- (a) Effectiveness. This is the most important evaluation criterion because it gauges the expected level of treatment of the technology. At a minimum, the technology must remove metals from the soil or reduce the mobility of the metals to render the soil nonhazardous by the TCLP and EP Toxicity test. Since more stringent standards may be imposed in future regulations or on a site specific basis, technologies which exceed the EP Toxicity target and achieve almost complete metal removal or immobilization are preferred.
- (b) Long-term performance. This criterion is linked to the earlier one on effectiveness. Any technology selected for remedying a contamination problem at a site must be effective over the long-term. Technologies which remove the metals from the soil or permanently render the soil nonhazardous would be preferable compared to those which yield a product susceptible to environmental attack or degradation and eventual release of metals to the environment.
- (c) Residual treatment/disposal requirements. If the application of a technology results in the generation of a residual waste stream, then this waste stream would require treatment or disposal in an appropriate manner. This additional treatment/disposal requirement would increase the complexity and/or overall cost of the technology. A technology which has minimal or no residual waste treatment/disposal requirements would be preferable from an environmental, operations, and cost standpoint.
- (d) Throughput. Technologies chosen for implementation must be capable of processing large quantities of soil in a short period of time if they are to be successfully implemented on the largest sites. Longer processing times result in higher overall operating costs.



- (e) Material handling. A technology which requires extensive soil pretreatment and materials handling would be more complicated and expensive. Some technologies may require pretreatment steps, such as screening, size reduction, or drying, prior to introduction to the treatment process. Technologies which do not require pretreatment may be less expensive and easier to implement and operate.
- (f) Air controls. Some technologies may result in air pollutant emissions which could require that control measures be implemented. This would increase the complexity and the cost of soil treatment in addition to requiring air emission permitting or approvals.
- (g) Flexibility. Many Army sites have soils which are contaminated with both volatile organic compounds (VOC's) or explosives and metals. In addition, many installation production facilities generate metal contaminated sludges. A technology which is capable of treating all of these types of soils and sludges or could be readily combined with explosives and VOC-contaminated soil treatment technologies would prove to be more widely applicable and cost-effective.
- (h) Ease of operations and maintenance. A technology which is simple and easy to operate would require a minimum amount of training and lower operating labor costs. Low maintenance requirements would also contribute to lower operating costs. Some novel technologies could require extensive training of the operators and technicians and high levels of operating efforts, since they are not well demonstrated, established technologies.
- (i) Transportability. This criterion is designed to assess the ease of relocating the process equipment from site to site. A technology which uses equipment which can be relocated with a low-level of effort for dismantling and reassembly would be preferable. Ideally, process equipment should either be truck- or skid-mounted units to enable easy movement. However, truck-mounted operation may not be possible in certain instances because of size, structural (weight) problems, or equipment complexity. The installation costs for readily transportable units would be lower and the equipment could be reused at other sites with lower dismantling and reinstallation costs.



- (j) Reliability. A technology which uses equipment with a high degree of reliability will result in shorter down times and lower overall costs. New and emerging technologies may require unique equipment which may be subject to upsets, be overly sensitive to feed quality or may not have a proven track record for reliability.
- (k) Safety. Potential risks include uncontrollable releases of hazardous substances or the use of corrosive, flammable or toxic chemicals. Safety concerns would have to be addressed by taking the necessary precautions in design and operation, and by providing the appropriate training and equipment. A technology which poses a serious threat to the health and well-being of the operators and site workers during or after implementation, would not be preferred.
- (l) Environmental risk. This criterion is designed to gauge the risk of environmental damage which might occur during implementation. This could range from fugitive emissions during soil handling to unplanned uncontrollable emissions of hazardous substances. If the environmental risk is low, the liability associated with implementation will be reduced.
- (m) Development time. From an implementation standpoint, it would be preferable to use a technology which requires minimal research and development effort. Technologies which require extensive research and development work prior to their implementation could not be applied on installations scheduled for near-term remedial action. Research and development costs would also be higher.
- (n) Proprietary status. A technology which is proprietary would require some form of licensing agreement with the firm that has a patented process or has withheld extensive development and design data. Licensing or royalty payments would increase the costs of implementing the technology. A technology which is in the public domain would be easier to implement as there are no licensing or patent constraints.
- (o) Permit/institutional. A technology which has demonstrated standards of performance and falls under existing guidelines or regulations (e.g., hazardous waste incineration) would be preferred by regulatory agencies. Regulatory agencies/institutions are generally very cautious with respect to the use of new technologies which are not proven and may result in lower levels of performance. Institutional or public opposition may lead to expensive delays in implementing a cleanup.

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- (p) Project cost. The treatment costs for each technology will be projected and compared to a benchmark cost for an established technology. The most widely accepted, established technology is excavation and off-site disposal at a secure landfill. If the cost for a new/emerging technology is significantly greater than the cost for excavation and secure landfill disposal, it is less desirable and would only be pursued if it offered clear advantages in long-term performance and overall environmental risk. Alternatively, a technology which offers the potential for lower cost may be investigated even though performance is uncertain prior to development.

As indicated previously, the three technologies were evaluated using the above criteria. A score of 1 to 3 was assigned to each evaluation criterion. Table 16 summarizes the criteria and the basis for assigning the numerical scores. Table 17 shows the methodology for determining the relative importance of the evaluation criterion and assigning corresponding weighting or "ranking" factors.

6.2 Microencapsulation.

- (a) Effectiveness. In this application of microencapsulation, the metals contaminated soils are dispersed and permanently immobilized in the asphalt soil product. Experimental data for treatment of similar wastes such as electroplating sludge indicate that the asphalt/soil product passes the EP Toxicity test leachability criteria. Therefore, the soil is likely to be rendered nonhazardous. This process has also been commercialized and operated to prove this effectiveness at full-scale proportions, although it has not been applied to the treatment of soils containing metals.
- (b) Long-term performance. The hardened asphalt/soil product is likely to be stable over a long term period. Asphalt produces a stable product which is resistant to leaching (reportedly 100 times more leach resistant than cement or pozzolanic solidification agents), chemical and biological attack, and mechanical stresses. Tests show that the product is less permeable than concrete. Asphalt does become brittle over time due to loss of its more volatile constituents and physical (loading) stresses. This could cause large scale cracks but should not result in significant impacts at the microscopic level. Further, these effects would be minimized with proper design of the disposal area. Accordingly, the metals in the soil should be held in the asphalt matrix resulting in their long-term immobilization.

TABLE 16
GUIDELINES FOR SCORING EVALUATION CRITERIA

Criterion number	Score of 3	Score of 2	Score of 1
1. Effectiveness	Demonstrated or probable ability to remove metals or otherwise render soil and waste nonhazardous.	Demonstrated or expected moderate performance, may require further treatment to render nonhazardous.	Little or no improvement likely (candidate fails).
2. Long-term Performance	Metals removed or permanently rendered non-hazardous.	Stability likely, but long-term changes in environmental conditions could result in release.	Effects of treatment expected to be transitory.
3. Residual Management	Produces no residual waste streams requiring treatment or disposal.	Produces residual wastes which can be readily treated and rendered nonhazardous.	As yet unidentified treatment of land disposal of residues is necessary.
4. Throughput	Demonstrated ability to process large volumes of material.	Potentially adaptable to process large volumes of material.	Demonstrated or potential limitations to volume of material processed.
5. Material Handling	Minimal handling; in situ process.	Requires excavation and/or some pretreatment (e.g., size reduction or slurry formation). No post treatment required.	Requires considerable pretreatment, and/or special equipment prior to entering processor. Process requires both pre- and post-treatment.
6. Air Controls	No emissions, requires minimal monitoring to ensure process stability.	Emissions easily controlled with minimum of standard equipment. Monitoring limited few specific compounds.	Require elaborate emissions control and monitoring.
7. Flexibility	Can also treat sludges, treat for organics or is easily linked with other.	Unknown capability to be linked with other unit processes.	Cannot be easily linked with other unit processes.
8. Ease of O&M	Simple operation, minimal maintenance requirements, no specialized training required.	Substantial operation and maintenance complexity but utilizes established techniques and training.	Novel process requiring specialized technicians and training for operation or maintenance.
9. Transportability	Requires minimal amount of dismantling and reassembly for moving. Most equipment is either truck- or skid-mounted.	Requires a moderate amount of dismantling and reassembly for movement. Some equipment is either truck- or skid-mounted.	Requires substantial dismantling and reassembly for transport. Major equipment is cumbersome. Very few process units are skid-mounted.
10. Reliability	Demonstrated high equipment reliability.	Moderate reliability estimated or known.	Hardware reliability unknown or potentially limited by unique equipment.
11. Safety	No hazard to workers or local residents during or after operations.	Hazardous conditions controlled presenting minimum threat to local residents.	Potential uncontrolled hazards to workers or local residents during or after operation.
12. Environmental Risk	Poses little environmental risk of contaminant migration during treatment.	Treatment may mobilize contaminants but the process is designed to contain and recover them.	Process mobilizes contaminants and poses a significant risk of uncontrolled release (candidate fails).
13. Development Time	Process requires only pilot scale or demonstration testing.	Process requires bench studies to further evaluate feasibility and refine conceptual design.	Basic long-term research required.
14. Proprietary Status	In public domain.	In public domain, but proprietary variations exists.	Proprietary.
15. Permit/Institutional	Process fits into existing regulatory guidelines/no institutional barriers anticipated.	Novel technology that does not fit existing guidelines and/or minor performance/institutional issues.	Novel technology with questionable performance. Considerable resistance to process use anticipated.
16. Projected Cost	Estimated unit cost less than disposal in secure landfill.	Approximately equal to disposal in secure landfill.	Greater than disposal in secure landfill.

TABLE 17. METHODOLOGY FOR RANKING EVALUATION CRITERIA

	1. Treatment effectiveness	2. Long term stability performance	3. Residuals treatment/disposal requirements	4. Materials throughput rate	5. Materials handling/pre-treatment requirements	6. Air emission control requirements	7. Flexibility	8. Ease of operation/maintenance	9. Transportability	10. Reliability	11. Safety	12. Environmental risk	13. Development time	14. Proprietary status	15. Permit/institutional issues	16. Projected treatment cost (\$/ton or present worth)	Total	Normalized Value	Rounded Rating Factor
1. Treatment effectiveness	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	15	4	4
2. Long term stability performance	0	1/2	1	1	1	1/2	1	1	1	1	1	1/2	1	1	1/2	1/2	12	3.2	3
3. Residuals treatment/disposal requirements	0	1/2	1	1	1	1	1/2	1	1	1	1/2	1/2	1	1	1	1/2	12.5	3.3	3
4. Materials throughput rate	0	0	0	1	1/2	1/2	1/2	1	1/2	1/2	1/2	0	1/2	1	1	0	7.0	1.9	2
5. Materials handling/pre-treatment requirements	0	0	0	0	1/2	1/2	1/2	1/2	1/2	0	0	0	0	1/2	0	0	2.5	0.6	1
6. Air emission control requirements	0	0	0	1/2	1/2	1/2	1/2	1/2	1/2	0	0	0	0	1/2	0	0	2.5	0.6	1
7. Flexibility	0	1/2	1/2	1/2	1/2	1/2	1/2	1	1/2	1/2	1/2	0	1	1	1	0	0	2.1	2
8. Ease of operation/maintenance	0	0	0	0	1/2	1	0	1/2	1/2	1	0	0	0	1/2	1	0	3.5	0.9	1
9. Transportability	0	0	0	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1	1	1	0	7.5	2	2
10. Reliability	0	0	0	1/2	1	1	1/2	1	1/2	1/2	1/2	1/2	1	1	1	0	8.5	2.3	2
11. Safety	0	0	1/2	1/2	1	1	1/2	1	1/2	1/2	1/2	1/2	1	1	1	1/2	9.5	2.6	3
12. Environmental risk	0	1/2	1/2	1	1	1	1	1	0	1/2	1/2	1	1	1	1	1/2	10.5	2.8	3
13. Development time	0	0	0	1/2	1	1	0	1	0	0	0	0	1/2	1	1	0	5.0	1.3	1
14. Proprietary status	0	0	0	0	1/2	1/2	0	1/2	0	0	0	0	1/2	1/2	1/2	1/2	3.0	0.8	1
15. Permit/institutional issues	0	0	0	0	1	1	0	0	1	0	0	0	0	1/2	1/2	1/2	4.0	1.0	1
16. Projected treatment cost (\$/ton or present worth)	0	1/2	1/2	1	1	1	1	1	1	1	1/2	1/2	1	1/2	1/2	1/2	11	2.9	3

Rating System

Ranking System

Assignment of Rating Factor

1 - Criterion is comparatively more important than that numbered above
 1/2 - Criterion is equally important
 0 - Criterion is less important

0.5 - 1.5 = 1
 1.5 - 2.5 = 2
 2.5 - 3.5 = 3
 3.5 - 4 = 4

Rating factors rounded off to total approximately 33 to result in maximum total score of approximately 100.



- (c) Residual treatment/disposal requirements. Overall, the process does not yield any hazardous waste/residue streams. The asphalt product from microencapsulation hardens to a solid asphaltic material on cooling, which, if nonleachable, can be disposed of in a nonhazardous landfill. Because it is nonhazardous, the long-term environmental liability is significantly less as compared to landfilling a hazardous waste (i.e., nontreated, excavated, contaminated soil). In this application the product could be considered for backfilling in the soil excavation area. Other options include allowing the product to cool in low cost containers or molds (i.e., cardboard containers) and disposing of the product in a nonhazardous (i.e., municipal) landfill. There is a possibility that the asphalt product may be constructively reused in applications such as paving, roofing, and similar general construction purposes. While this would greatly improve process economics, technical issues (such as the release of metals due to road wear), and institutional barriers may prevent constructive reuse in most applications. In the case of VOC's in the soils, the VOS's would be removed from the soil using LTS and oxidized in the steam boiler for the asphalt tanks.
- (d) Throughput. The technology utilizes conventional thermal processing and extruder equipment; therefore, high processing rates are possible. The largest extruder unit identified for this application can process over 100 tons per day or approximately three times the highest volume case evaluated. Multiple units can be used, if necessary, for very high throughput requirements.
- (e) Materials handling. The process requires excavation of the contaminated soil and pretreatment to produce a uniform feed material by removing and/or crushing oversize materials, like rocks and debris, to a particle size no larger than approximately 1/4 inch. Particles larger than 1/4 inch, the approximate extruder clearance, would ride on top of the screws, and therefore would not be incorporated into the asphalt matrix, or potentially cause equipment binding. This results in a more complex soil pretreatment process, including screening of the large (>2 in.) oversize particles and crushing the smaller ones in a gravel crusher. The larger particles could be backfilled in the excavation area, batch fed into the crusher (with higher operator attention and a

higher recirculation rate), disposed of off-site at a landfill, cleaned to remove attached soil and dirt, etc. The choice of these options would depend on site conditions and the quantity of the oversize particles. This process also requires drying the soil to approximately 1 percent moisture prior to feeding it to the extruder. The other handling operations are standard methods used in the road building and construction industry.

- (f) Air controls. Some particulates could be emitted from the dryer but it is expected that use of the LTTS unit for drying will produce little or no dust. Presently, a small baghouse is included in the design which can be used for the dust control of the water vapor outlet stream from the dryer. Fugitive dust emissions could also occur from the conveying, screening, and crushing of dried soil. If necessary, enclosures and dust collection devices could be applied.

In the case of VOC emissions from the drying of soils containing metals and organics, the stream can be fed to the steam boiler, if feasible, or a fume incinerator for destruction of VOC's.

- (g) Flexibility. This process can be used on various solid and liquid wastes and sludges, in many cases with minor process or operating modifications. Residues from organic and explosives treatment processes can be readily treated. In fact, the LTTS process for organics removal from soil is quite compatible with microencapsulation. The basic microencapsulation process can be utilized for treatment of soils that are contaminated with both metals and VOC's, by using the LTTS processor as the dryer in all applications.
- (h) Ease of operations and maintenance. The possibility exists of encountering some problems during the initial screening step with certain (i.e., wet, clayey) soils, depending on the particular site. This preliminary step is common to all three treatment technologies, however. Because of the small particle size requirement of the extruder mixer, the soil feed must first be screened/crushed to approximately 1/4 inch in size. Equipment meeting these requirements was identified; however, there is a possibility that some problems may be encountered in the field with this processing step. It is anticipated that the preheated soil stockpile at this point will provide inventory for continued extruder operation in the event of problems in this particle size reduction step.

In order to keep the total treatment process operating, it is also necessary that the asphalt supply continue to fill process requirements. Therefore, reliable asphalt sources must be identified at each application.

- (i) Transportability. The extruder and HOLOFLITE® dryer used in this process are skid-mounted units. The asphalt storage tanks are large and cannot be truck-mounted units. They would have to be transported in pieces and assembled at the site. A higher level of effort would be required for the higher soil processing rate (100,000 TPY). The crusher, required to reduce the soil particle size to 1/4-inch or less, would have to be transported in sections and assembled at the site. All other soil screening and handling equipment would be transportable units commonly used in the road-building industry.
- (j) Reliability. Overall, this process is expected to have a high degree of reliability. The soils handling equipment has been used extensively in the construction industry. The successful operation of the HOLOFLITE® thermal processor has been proven in the field for similar soils applications. The extruder has been proven to be highly reliable as used for the mixing of liquid wastes and asphalt in the VRS™ process for two decades, but remains to be proven for soils in general and soils with metals in particular. All other equipment in the process (i.e., boiler) are standard applications of proven and reliable equipment.
- (k) Safety. There are no unique or significant safety problems associated with this process. Normal precautions used in the construction industry will be required for the process operation. Excavation, transportation, and processing of the contaminated soils will have to be performed with the appropriate level of personnel protection. Handling of the hot asphalt feed stream and asphalt/soil product should include normal precautions associated with the handling of asphalt aggregate product.
- (l) Environmental risk. Overall, the environmental risks associated with this process are low. Implementation of the technology should not result in an uncontrollable release of hazardous substances to the environment. Potential air emissions associated with the hot asphalt at the product outlet of the extruder and fugitive dust emissions can be controlled, if necessary. This aspect should be investigated further, in the pilot study and detailed design phases of work.

- (m) Development time. This process is a fully commercialized technology, but has not been applied to metals contaminated soils. As a result, some bench-scale and pilot-plant tests are recommended to demonstrate performance in this application, to investigate process optimization (i.e., use of other binders on soil-binder ratio), to confirm nonleachability of solidified asphalt, and to verify the full-scale operating parameters before final design and implementation. Due to previous commercial application, full-scale implementation can occur with very short development time.
- (n) Proprietary status. This application of microencapsulation is based on the VRS™ process, which currently has a patent pending covering the extruder processing equipment and the asphalt binder composition (WasteChem recommends a particular grade of asphalt for the VRS process). Therefore, if the process patent is granted, licensing arrangements would have to be made. However, asphalt is a commercially available binder and alternate processes which would not infringe the VRS pending patent, might be developed.
- (o) Permit/institutional. The VRS™ process is a fully commercialized and proven system with an established record of performance for numerous applications. However, because the process has not been directly applied to soils contaminated with metals, pilot-scale tests will have to be done to prove that the asphalt/soil product is nonhazardous (i.e., pass the TCLP and EP Toxicity test). Emissions from the process (i.e., fugitive emissions from the asphalt/soil product end of the extruder, fugitive dust emissions from soil excavation/pretreatment, and water vapor/air emissions from the drying process) could require air pollution control permits.
- (p) Project cost. The costs projected for microencapsulation show that these costs are significantly higher than the typical cost for excavation and off-site disposal in an RCRA landfill for smaller quantities of soil (10,000 tons/year). The costs for larger quantities of soil (100,000 tons/year) are significantly lower than the smaller quantity case; however, they are still higher than the current cost for excavation and off-site RCRA landfill disposal. This is mainly due to the high operating costs associated with the large asphalt addition requirements of the process.

Each criterion for evaluation of microencapsulation was given a numerical score, as described Subsection 6.1. The overall score will be used for comparison with the other two technologies. A summary of these scores for microencapsulation is presented in Table 18.

6.3 Roasting.

- (a) Effectiveness. The technology results in the immobilization of the metals in the partially or fully vitrified glassy matrix referred to as slag. Experiments indicate that the slag would pass the EP Toxicity test leachability criterion.
- (b) Long-term performance. The slag resulting from this process should be very stable over the long-term. Experimental tests have shown that the fully glassified slag material has the same stability as granite. Apart from the low leachability characteristics, the product also exhibited good strength (physical) properties.
- (c) Residual treatment/disposal requirements. This process would not yield any hazardous waste/residue streams. The slag would be backfilled in the excavated areas or would be disposed in a nonhazardous landfill.
- (d) Throughput. Since the technology would use a conventional rotary-kiln as the roasting furnace, much like cement-making equipment, high processing rates are readily achievable. Standard kilns are available for the processing rates evaluated and range up to several thousand tons per day.
- (e) Materials handling. The process requires excavation of the contaminated soil and screening to remove oversize material like rocks and debris. This screening is necessary because the soil has to be mixed with kaolin (an additive) in a twin-shaft pugmill. This pugmill provides a thorough mixing and removal of particles >2-inch diameter is recommended by the manufacturers to ensure reliable operation. Options for dealing with the oversize particles include backfilling in the excavated area, off-site disposal at a landfill, cleaning to remove soil and dirt attached to the oversize particles, etc. The choice of these options would depend on the quantity of the oversize particles. All other handling operations are standard methods used in the road building/construction industry.
- (f) Air controls. The major pollutant emitted would be particulates (generated by agitation of soil in the kiln) which would be controlled using a baghouse. There is a possibility of metals (lead) vaporizing and condensing in the baghouse. The baghouse dust will be fed back into the hot end of the kiln to be incorporated into the slag. The effectiveness of returning the baghouse dust to the kiln would have to be demonstrated in the development program.

TABLE 18. SUMMARY OF EVALUATION SCORES FOR MICROENCAPSULATION

Criterion	Rating factor (RF)	Numerical score (NS)	Score NS*RF
1. Effectiveness	4	3	12
2. Long-term performance	3	2.5	2.5
3. Residual treatment/ Disposal requirements	3	2	6
4. Throughput	2	2.5	5
5. Materials handling	1	1.5	1.5
6. Air controls	1	2	2
7. Flexibility	2	3	6.
8. Ease of operation and maintenance	1	2	2
9. Transportability	2	2.5	5
10. Reliability	2	3	6
11. Safety	3	2	6
12. Environmental risk	3	3	9
13. Development time	1	2	2
14. Proprietary status	1	1.5	1.5
15. Permit/institutional	1	2	2
16. Project cost	3	1	3
Total score			76.5



- (g) Flexibility. The concept design focuses on the treatment of soils contaminated with metals only. However, the process can be used to treat soils contaminated with metals and VOC's. One of the options considered was the removal of VOC's by LTTS and subsequently treating the soils for metals by roasting. There is also the possibility of designing for an elevated kiln air exit temperature or of co-currently firing the contaminated soil in the kiln which would result in the destruction of organics at high temperature. Process optimization for this application should be explored during the R&D phase. Adaptation of the process to explosives-contaminated soil would require some modifications to the process. Sludges and other waste streams could also be handled by the process.
- (h) Ease of operations and maintenance. Operation and maintenance requirements, similar to those encountered in the cement industry, are not extremely complex. At the high operating temperatures, there is a possibility that the molten slag could solidify and build up on the walls of the kiln. This buildup would require periodic maintenance shutdowns for removal.
- (i) Transportability. The rotary kilns which would be utilized in the roasting process would be large units which cannot be easily transported. They would have to be disassembled and transported in sections and would require substantial disassembly and assembly time for relocation to a new site. All other soil preparation and handling equipment would be standard portable units used in the road-building industry. Some ancillary equipment such as large fuel oil storage tanks, etc., would have to be transported in sections and require some assembly time at the site.
- (j) Reliability. Most of equipment proposed for this process are used in the cement and construction industries with a high degree of reliability.
- (k) Safety. There are no unique safety problems associated with this process. Normal safety precautions similar to those used in the cement industry would be required for the rotary kiln operations. Excavation and processing of the contaminated soils would have to be performed with the appropriate level of personnel protection.
- (l) Environmental risk. Implementing this technology would not result in uncontrollable emissions of hazardous substances. There is a possibility of certain metals being volatilized and this is controlled by the addition of kaolin and recycling the baghouse dust to the kiln.



- (m) Development time. Extensive bench-scale and pilot-plant tests would have to be performed to establish full-scale operating parameters and demonstrate performance. These tests would include process optimization studies.
- (n) Proprietary status. No patents for this technology are known to exist. It is in the public domain. The potential exists for patenting unique process approaches or equipment which may emerge from a development program.
- (o) Permit/institutional. Roasting is a new technology and does not have an established regulatory performance standard. Pilot-scale tests would have to be performed to demonstrate that the product is nonhazardous. Particulate emission controls may require air pollution control permits.
- (p) Project cost. Cost estimates show that these costs are likely to be higher than the cost for excavation and off-site RCRA landfill disposal for smaller quantities of soil (10,000 TPY). However, the costs for larger quantities of soil (100,000 TPY) may be comparable to those for excavation and off-site disposal.

Each criterion for evaluation of roasting was given a numerical score, as described in Subsection 6.1. The overall score will be used for comparison with the other two technologies. A summary of these scores for roasting is presented in Table 19.

6.4 On-site extraction.

- (a) Effectiveness. Extraction is expected to result in the removal of metals from the soil below the minimum target concentration (below the TCLP and EP Toxicity criteria), but this has not been demonstrated in the laboratory or in pilot-scale work for a wide range of metals and feed conditions.
- (b) Long-term performance. The removal of metals, if initially successful, would render the soil permanently nonhazardous. The product is thus stable over the long term.
- (c) Residual treatment disposal. The process requires that the overflow from the first thickener be treated in a wastewater treatment system to remove the metals so that the solution can be reused in the fifth thickener. This would result in the generation of a metal bearing sludge waste stream from the wastewater



TABLE 19. SUMMARY OF EVALUATION SCORES FOR ROASTING

Criterion	Rating factor (RF)	Numerical score (NS)	Score NS*RF
1. Effectiveness	4	3	12
2. Long-term performance	3	3	9
3. Residual treatment/ Disposal requirements	3	2.5	7.5
4. Throughput	2	3	6
5. Materials handling	1	2	2
6. Air controls	1	2	2
7. Flexibility	2	2.5	5
8. Ease of O&M	1	2	2
9. Transportability	2	1	2
10. Reliability	2	3	6
11. Safety	3	2	6
12. Environmental risk	3	3	9
13. Development time	1	1.5	1.5
14. Proprietary status	1	3	3
15. Permit/institutional	1	1.5	1.5
16. Project cost	3	2	6
Total score			80.5



treatment system. The wastewater treatment system approach would be re-evaluated and a final technology would be selected during the process optimization phase of the R&D program. The selection would be based in part on factors such as the quality and quantity of sludge generated and the ability to match the extraction process requirements (e.g., pH, salinity of recycled solution). This sludge may itself be a hazardous waste and, therefore, would have to be further treated or disposed appropriately. The treated soil (product) would either be backfilled in the excavated area or in a nonhazardous landfill.

- (d) Throughput. Since the process can utilize conventional mining industry and wastewater treatment equipment there are no anticipated problems with scaleup to higher processing rates.
- (e) Materials handling. The process involves excavation of the soil and screening to remove oversize material. This screening is necessary to ensure intimate mixing of the soil particles with the leaching/ extracting solutions and to prevent damage to the mixing, thickening, and transfer equipment and pumps. Excavation, screening, and size reduction require the use of conventional equipment including conveyors, hoppers, trommels etc. which are commonly used in the road-building industry. Movement of the thickener underflows which have a high solids content would require special pumps which are commonly used in the mineral extraction industry.
- (f) Air controls. This technology does not require air emission controls.
- (g) Flexibility. Acid extraction cannot be used to treat soils contaminated with VOC's and metals. The concept design focuses on the treatment of soils contaminated with metals only by extraction. One option that has been considered for the treatment of soils contaminated with VOC's and metals was to first remove the VOC's by LTTS and to subsequently remove the metals by acid extraction. It must be noted that there are other processes, including extractive froth flotation, which may be used to remove organics from the soil. Similarly, treatment of soils contaminated with explosives and VOC's would require sequential, rather than integrated, treatment. This process, as presently conceived, would not be applied to waste sludge treatment. The final selection of a combined treatment process should be made during the process optimization phase of the R&D program.



- (h) Ease of operations and maintenance. The process has a high level of operational complexity due to its multistage operation and wastewater treatment requirements, but the equipment and control systems are commonly used in the extractive metallurgy and wastewater treatment industries. No specialized operating techniques or training, other than those used in these industries, is required for the individual equipment. However, the operators responsible for the entire system would require special training.
- (i) Transportability. Most of the equipment used in Case 1 (10,000 TPY soil) would be fully-assembled truck-mounted units which require minimal assembly. However, for the higher soil processing rate (100,000 TPY), the equipment would have to be transported in parts and assembled at the site. The soil screening and handling equipment for both cases would be portable units commonly used in the road-building industry.
- (j) Reliability. Most of the equipment used in the process has a reasonable level of reliability and are currently used in the road building, extractive metallurgy and wastewater treatment industries.
- (k) Safety. There are minimal hazards associated with the process, with the exception of handling of acids. Personnel associated with acid handling would require training and use of protective gear. Excavation and processing of the soils must be performed by personnel attired in the appropriate safety gear.
- (l) Environmental risk. There is no increased risk of off-site migration of metals during the implementation of this process because the soil is excavated and treated in self-contained equipment. The wastewater treatment plant sludge must be disposed appropriately and may represent some long-term liability, if it is a hazardous waste requiring landfill disposal. The treated soils must be dewatered prior to disposal/backfilling.
- (m) Development time. This process requires bench-scale and pilot-plant testing before the engineering design can be completed and the technology implemented. It has been used in the metallurgical and mining industries (which provides a good base of information), but has not been used to treat soils with low levels of metals.
- (n) Proprietary status. Extraction of metals from soils using acid solutions is established technology in the extractive metallurgy industry and is in the public domain.



- (o) Permit/institutional. This technology is not proven or established and regulatory guidelines/performance standards have not been developed for it. Laboratory and, possibly, pilot-plant tests would have to be performed to show that the treated soil would meet the TCLP and EP Toxicity test criteria or other site-specific criteria. There may be some institutional/agency resistance to this technology because it is not demonstrated and performance standards have not yet been established. Treated wastewater, which has to be disposed, would either have to be trucked to an off-site facility or be discharged under an NPDES permit.
- (p) Projected cost. The estimated costs for the treatment of metal contaminated soil by extraction is higher than those for off-site disposal in a secure landfill for smaller quantities of soil (10,000 TPY). These estimates indicate that unit costs decrease as the quantity of soil processed increases because it is a capital intensive process. Large soil treatment applications (100,000 TPY) may be conducted at a cost comparable to that for the conventional excavation/off-site disposal approach. The total project costs are sensitive to reagent and sludge disposal costs which in turn are dependent on the initial metal concentrations in the contaminated soil. It must be noted that there is some uncertainty in the cost estimates due to the early stage of technology development. (See Subsection 5.1.3 for a full discussion.)

Each criterion for evaluation of on-site extraction was given a numerical score, as described in Subsection 6.1. the overall score will be used for comparison with the other two technologies. A summary of these scores for on-site extraction is presented in Table 20.



TABLE 20. SUMMARY OF EVALUATION SCORES FOR ON-SITE EXTRACTION

Criterion	Rating factor (RF)	Numerical score (NS)	Score NS*RF
1. Effectiveness	4	2	8
2. Long-term performance	3	3	9
3. Residual treatment/ Disposal requirements	3	1	3
4. Throughput	2	3	6
5. Materials handling	1	1.5	1.5
6. Air controls	1	3	3
7. Flexibility	2	2	4
8. Ease of operations and maintenance	1	1.5	1.5
9. Transportability	2	2	4
10. Reliability	2	2	4
11. Safety	3	2.5	7.5
12. Environmental risk	3	2	6.0
13. Development time	1	1.5	1.5
14. Proprietary status	1	3	3
15. Permit/institutional	1	1	1
16. Project cost	3	2	6.0
Total score			69

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions. An extensive literature and data base search identified 21 potentially viable technologies for the treatment of metals contaminated soils. Most of these were new or emerging technologies. A preliminary screening evaluation of these technologies was made based on key technical feasibility criteria. Three technologies were selected for a more detailed evaluation: microencapsulation, roasting, and extraction.

Preliminary conceptual designs, flow sheets, and cost estimates were prepared for the three technologies as a basis for a more detailed evaluation and comparison. The evaluation was conducted using both cost and noncost criteria, including expected performance and development and implementation issues. In order to summarize and quantify the evaluation presented in Section 6, each technology was numerically rated for each criterion. These numerical scores are tabulated in Table 21, providing a concise comparison between technologies for each criterion. The advantages, disadvantages and uncertainties of each technology are summarized on Table 22.

The following conclusions were made at the end of the technology evaluations:

- (a) The numerical scores for the three technologies were relatively close. Roasting was ranked highest, followed by microencapsulation and extraction.
- (b) This ranking is consistent with the preliminary evaluation rankings in Section 4.
- (c) Roasting is expected to generate the most stable, low mobility product which should exceed treatment objectives.
- (d) Microencapsulation is expected to easily meet treatment objectives, with perhaps lower stability and slightly higher mobility than roasting.
- (e) Extraction would remove metals from the soil matrix but its effectiveness has yet to be demonstrated.
- (f) From a cost-effectiveness standpoint roasting would be best suited for high soil treatment rates.

TABLE 21. COMPARATIVE RANKING OF TECHNOLOGIES

Criteria/technology	Rating factor	Microencapsulation	Roasting	Extraction
1. Effectiveness	4	3	3	2
2. Long-term Performance	3	2.5	3	3
3. Residual treatment/disposal	3	2	2.5	1
4. Throughput	2	3	3	3
5. Materials handling	1	1.5	2	1.5
6. Air controls	1	2	2	3
7. Flexibility	2	3	2.5	2
8. Ease of operations and maintenance	1	2	2	1.5
9. Transportability	2	2.5	1	2
10. Reliability	2	3	3	2
11. Safety	3	2	2	2.5
12. Environmental risk	3	3	3	2
13. Development time	1	2	1.5	1.5
14. Proprietary status	1	1.5	3	3
15. Permit/institutional	1	2	1	1
16. Project cost	3	<u>1</u>	<u>2</u>	<u>2</u>
Total numerical score		76.5	80.5	69

TABLE 22. SUMMARY OF INDIVIDUAL TECHNOLOGY EVALUATIONS

Technology	Advantages	Disadvantages	Uncertainties
1. Micro-encapsulation	<p>Metals are permanently immobilized in the asphalt product which should be non-hazardous and is resistant to chemical and biological attack.</p> <p>Process is commercialized and can be implemented with less time needed for development.</p> <p>Process can handle both organics and inorganics with very little modification and there is no need for additional treatment equipment.</p> <p>Process can accept feeds with various amounts of moisture content with little modification in the drying step.</p> <p>Process utilizes conventional and/or full-scale proven construction, drying, and extruding equipment.</p> <p>All process equipment readily transportable.</p>	<p>Materials handling requirements are more complex than the other two technologies as drying and size reduction are required. The process cannot tolerate any material larger than 1/4 in. in diameter.</p> <p>The operations and maintenance costs and unit costs are dependent on the amount of asphalt used in the process.</p> <p>Asphalt costs are relatively high, therefore, significant economies of scale are not achieved with higher processing rates.</p> <p>Estimated costs are higher than those for secure landfill disposal and other technologies evaluated.</p>	<p>Process has not been applied to the treatment of soils contaminated with metals.</p> <p>Laboratory tests are necessary to verify product quality and process operating parameters.</p>
2. Roasting	<p>Metals are permanently immobilized in a nonleachable and stable glass matrix. Product should be rendered nonhazardous and very stable.</p> <p>Capital costs are high but economies of scale can be achieved; unit costs are significantly reduced when soil processing rates are high, potentially comparable with the costs for off-site disposal in a secure landfill.</p>	<p>Full-scale commercial processes are not available in the United States.</p> <p>Energy requirements are high.</p> <p>Large kilns are needed and this reduces the mobility of the process.</p> <p>Process has to be modified to handle organics.</p>	<p>Additive compositions, soil/additive ratios and process operating conditions need to be established by performing extensive laboratory and pilot-plant tests.</p>

TABLE 22. (CONTINUED)

Technology	Advantages	Disadvantages	Uncertainties
On-site extraction	<p>Process would be applicable to a wide variety of soils.</p> <p>Proposed method/design utilizes conventional construction and cement manufacturing equipment.</p> <p>Process results in the removal of metals in soils rendering the soils nonhazardous.</p> <p>Proposed method utilizes conventional techniques and equipment used in the mining industry.</p> <p>Economies of scale are achieved with higher soil processing rates - unit costs are potentially lower than those for off-site disposal in a secure landfill.</p>	<p>Process conditions must be tested/adjusted for each site's type of soils and metal compounds.</p> <p>Organics cannot be handled by the process. Add-on treatment process is needed to treat soils with organics.</p> <p>Full-scale operational data is unavailable.</p> <p>Process yields a residual wastewater treatment sludge which must be treated or disposed of, possibly as a hazardous waste.</p> <p>Project costs are sensitive to reagent and sludge disposal costs, which in turn are dependent on initial soil metal concentrations.</p>	<p>Performance must be demonstrated on the laboratory- and pilot-scale.</p> <p>Completeness of extraction must be demonstrated.</p> <p>Reagent usage and type must be determined.</p> <p>The optimum extract solution treatment process must be selected and tested.</p>

- (g) The roasting process could probably be modified with little effort to treat soils with VOC's and metals. Minor design modifications to an existing rotary kiln used to incinerate organics to achieve roasting conditions, would result in the metals being immobilized in the ash.
- (h) Microencapsulation would require lower capital outlay but operating costs would be relatively high due to the high cost of raw materials (asphalt).
- (i) While the expected level of performance of micro-encapsulation may be high, better performance could probably be achieved at a lower cost with another technology (i.e., roasting).
- (j) While the ability of extraction to achieve the required performance is as yet uncertain, technology could be cost-effectively transferred from the extractive metallurgy industry for this operation.
- (k) Extraction costs are sensitive to soil metal concentrations. Lower costs may be achievable for those limited cases where soil metals concentrations are low or metal species are more readily extractable. For the case analyzed, extraction does not offer significant cost advantages over roasting, the technology anticipated to be more effective.

7.2 Recommendations. Of the three technologies evaluated in greater detail, roasting should provide the most effective treatment. Due to its high capital cost, it would be cost competitive with conventional off-site disposal only at higher process throughputs. Roasting can also be adapted to effectively treat soils containing both organics and metals and explosives and metals.

Extraction has the potential for providing cost-effective treatment for certain metal-contaminated soils. The total project costs are sensitive to the costs for wastewater treatment and sludge disposal which in turn are dependent on the metal concentrations in the contaminated soils at various Army installations. The total project costs are comparable to roasting. However, given the uncertainty in treatment performance and the sensitivity to soil metal concentrations, further research and development is not recommended for the extraction technology.

Microencapsulation should be more effective, reliable, and flexible in treating soils contaminated with metals when compared to extraction. However, the estimated costs are significantly higher than those for extraction, and roasting technologies, primarily because of the high cost of raw materials. These projected costs are also not competitive with those for existing conventional technologies/methods. Therefore, further research and development is not recommended.



In conclusion, WESTON recommends further USATHAMA developmental efforts for roasting. A laboratory test plan will be developed for this novel technology as the final subtask of this study under Task Order 7.



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